Understanding How Generative AI Cultivates Self-Directed Learning Capabilities: A Perspective Based on Digital Technology Evolution

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Abstract
The use of digital technologies to support student learning has become a trend in the field of education. However, whether digital technologies can effectively facilitate students' self-directed learning remains a topic of debate in academia. This study employs a meta-analytic approach to examine the effectiveness of digital technologies in promoting self-directed learning among students, while exploring the influence of different moderating variables. A total of 27 articles (including 30 independent studies with 3,711 participants) met the inclusion criteria. The results indicate that digital technologies significantly enhance students' self-directed learning, demonstrating a moderate effect size (Hedges's g = 0.778, 95% CI: 0.510–0.847, $p < 0.05$). Among the moderating variables, the type of digital technology and teaching size showed significant effects, whereas educational stage, subject area, and intervention duration did not exhibit significant moderating effects. Based on the findings, recommendations are proposed regarding the selection of digital technology types, adjustments to teaching size and intervention duration, and targeted considerations for educational level and subject area. This study provides a theoretical foundation and empirical evidence for the scientific application of digital technologies, the cultivation of self-directed learning, and the formulation of educational technology policies.
Keywords: digital technologies, meta-analytic, self-directed learning

1 INTROUCTION

As online education opportunities expand and digital technologies such as artificial intelligence (AI) advance rapidly, self-directed learning (SDL) has emerged as a fundamental skill for individuals to adapt and succeed in the digital era(Morris, 2019) . This shift has also established SDL as an indispensable component of contemporary education(Aulakh et al., 2025) . SDL emphasizes learners' ability to proactively set goals, select strategies, monitor progress, and evaluate outcomes, monitor progress, and evaluate outcomes. In the digital era characterized by rapid knowledge iteration, the significance of SDL has become even more pronounced(Gaol & Prasolova-Førland, 2022). SDL can cultivate students' self-awareness, goal orientation, and sense of mastery during the learning process. These competencies enhance learners' motivation, engagement, and confidence in digital learning environments(Morrison & McCutheon, 2019). Meanwhile, the explosive development of digital technologies - from mobile learning platforms to virtual reality systems and today's generative artificial intelligence - has provided learners with unprecedented learning resources and educational experiences(Gaol & Prasolova-Førland, 2022). Currently, a growing number of educators are integrating digital tools into traditional instructional environments and developing innovative teaching models(Morrison & McCutheon, 2019).

However, the actual efficacy of applying digital technologies to foster students' SDL remains debated. One view is that digital technology can facilitate the development of students' SDL(Lingling, 2024; Rashed Ibraheam Almohesh, 2024). But another view suggests that the role of digital technology in cultivating students' SDL is negligible or even nonexistent(Lee, 2024; Yeh et al., 2022). Existing studies have inconsistent conclusions findings due to differences in samples and technological tools, etc. Therefore, there is a need to integrate existing evidence through meta-analysis to quantify the overall effect of digital technology on SDL and explore key moderating variables to compensate for the limitations of single studies.

Therefore, this study aims to comprehensively evaluate the impact of digital technology on students' SDL through a meta-analysis approach and investigated whether educational stage, subject area, digital technology type, intervention duration, and teaching size moderated the impact of digital technology on students' SDL. This study can provide a theoretical basis and empirical evidence for the scientific application of digital technology, the cultivation of SDL and the development of educational technology policies.

2 LITERATURE REVIEW

2.1 Self-directed learning and digital technology

So far, there is no unified and clear definition of SDL. Based on previous research, perspectives on SDL can be broadly categorized into the capability view and the process view. From the perspective of ability, self-directed learners are able to initiate learning on their own and sustain it independently. Self-directed learners also possess the capacity for self-training, a strong desire for learning, and confidence in their learning abilities. Self-directed learners can apply fundamental learning techniques and strategies, organize appropriate learning steps, and formulate as well as execute learning plans accordingly(Guglielmino, 1977). SDL represents a capability that is particularly crucial for successful living and working in the modern world, offering learners a heightened level of adaptability to constantly changing social and environmental conditions(Jossberger et al., 2010). In addition, from the perspective of process, SDL is a process in which individuals actively, with or without the help of others, judge their own learning needs, formulate learning objectives, determine learning resources, choose learning strategies, implement learning activities, and evaluate learning outcomes(Knowles, 1975). In this process, learners are responsible for controlling their own learning objectives and means to meet the perceived needs of personal goals or the personal environment(Morris, 2019).

Based on the background and requirements of this study, SDL is regarded as a capability in this research. Self-directed learners are capable of autonomous planning, resource integration, strategy selection, and self-evaluation. That is, learners possess the ability to actively judge learning needs, independently set learning objectives, choose learning resources, carry out learning activities, and assess learning outcomes.

Although SDL emphasizes the autonomy and independence of learners, it does not mean that learners study in isolation or are completely cut off from the outside world. Although existing studies have shown that one of the basic elements to support and enhance SDL is assistance, especially the feedback provided by educators, this requires educators to spend a lot of time and energy(Stockdale & Brockett, 2011). The emergence of digital technology has brought great convenience to educators. With the advent of the digital era, the advantages of digital technology have become increasingly evident, especially in the field of education. Digital technologies such as information and communication technology, artificial intelligence, big data, and cloud computing have made the development of many new products in the field of education possible, including software, platforms, and devices(Tang et al., 2022). Digital technology is an open door to new learning methods and choices, which may be beneficial to the improvement of learners' abilities(Schneckenberg et al., 2011). Digital technology has the potential to support students in achieving self-direction, especially by combining SDL and technology to provide sufficient support(Morris & Rohs, 2023). From the development of digital technology to the present, there is a close relationship between the use of digital technology and SDL. SDL has been enhanced and facilitated through technologies such as Web2.0. Web2.0 provides learners with a convenient platform for critical reflection and interaction with social network agents(Anderson, 2007). In the modern world, the interactive functions of generative artificial intelligence (GenAI) encourage student engagement and active learning(Brown et al., 2020). The personalized functions of GenAI can be used to effectively provide tailored learning support(Gilson et al., 2023). The assessment function of GenAI is also capable of evaluating students' learning outcomes and providing feedback, which helps students identify their deficiencies(Chiang et al., 2024). Through these means, digital technology offers students important opportunities to improve their learning abilities and develop relevant skills.

Teaching supported by digital technology can enhance students' participation and enthusiasm in learning, improve their metacognitive and self-monitoring abilities, increase their focus and intrinsic motivation for learning, thereby promoting the development of SDL. For example, Lingling (2024)explored the impact of virtual simulation technology on students' SDL through a quasi-experimental study. The research found that, compared to the control group using traditional teaching methods, the experimental group supported by virtual simulation technology showed a significant improvement in SDL. Rashed Ibraheam Almohesh (2024) employed a quasi-experimental design to evaluate the impact of ChatGPT on the SDL of 250 primary school students from six schools in Riyadh, Saudi Arabia. The results indicated that students in the experimental group who utilized ChatGPT demonstrated higher levels of SDL, suggesting that digital technology plays a positive role in enhancing SDL.

The development of digital technology has sparked excitement while also raising concerns among some people. While digital technology provides numerous conveniences for learners, it may also weaken their basic learning abilities(Hedges, 1981). Excessive reliance on digital technology by learners can lead to a lack of critical thinking(Cooper, 2023) and hinder their independent thinking(Bozkurt et al., 2023). Additionally, when learners are subjected to monitoring through technologies such as data tracking, their anxiety levels may increase, which in turn affects the development of SDL. Although these technologies can enhance learners' short-term engagement, they undermine learners' long-term intrinsic motivation for learning, ultimately hindering the development of learners' SDL. For example, Yeh et al. (2022) investigated the impact of the e-STORY App on SDL among 77 nursing students using a quasi-experimental approach. The experimental results showed that there

was no significant improvement in SDL among the students who used the e-STORY App compared to those in the control group who received traditional teaching. Lee (2024) explored the effectiveness of using ChatGPT as a feedback tool for English job letter writing among 51 Korean university students in a business English course. Survey and interview data indicated that, although students generally expressed satisfaction with the feedback process, its impact on developing SDL was limited. Therefore, it is necessary to clearly explore the impact of digital technology on students' SDL.

2.2 Relevant studies

In recent years, researchers have conducted various reviews and meta-analyses to explore the application of digital technology in the field of education. For example, Zhang et al. (2022)conducted a meta-analysis to study the effectiveness of augmented reality technology in K-12 education for learning outcomes. The research results showed a large overall effect size (g=0.919), indicating that the use of augmented reality has a significant positive impact on the learning outcomes of K-12 students. Ma et al. (2024)employed a literature review method to study the learning effects of nursing undergraduates using digital technology in clinical education. The results indicated that the application of digital technology in clinical education is beneficial to the learning of nursing undergraduates. Sailer et al. (2024)conducted a systematic review of 25 meta-analyses that explored the impact of digital technology on teaching effectiveness. The results showed that the use of digital technology does not in itself change student learning outcomes in higher education. However, when digital technology provides support for specific learning activities, such as flipped classrooms and collaborative learning, learners' cognitive learning outcomes are improved.

In addition, some reviews and meta-analyses have begun to focus on the application of digital technology in cultivating students' specific learning abilities and thinking competencies. Fadda et al. (2022)carried out a meta-analysis to investigate the impact of digital games on the mathematical learning motivation of K-12 students. The research showed that compared with traditional teaching practices, digital games are effective tools in enhancing the mathematical learning motivation of K-12 students (g=0.27). Lan and Zhou (2025)utilized a literature review to explore the role of artificial intelligence applications in self-regulated learning among higher education students. The results demonstrated that artificial intelligence has the potential to promote the deliberate thinking, performance, and reflection phases of self-regulated learning. Seenivasan (2024)reviewed literature on the application of information and communication technology (ICT) in school education. He found that the use of ICT helps students access digital information and course content effectively and efficiently. ICT supports student-centered learning and the development of creative learning environments, providing more opportunities for critical thinking skills.

In general, most of the existing literature reviews and meta-analyses have only explored the impact of digital technology on dimensions related to SDL (such as learning motivation), and there is a lack of research on if digital technology supports the cultivation of SDL. Furthermore, the research is concentrated on specific subjects (such as mathematics, medicine) or educational levels (such as K-12, university). Moreover, previous meta-analyses also lacked research on moderating variables that may affect the impact of digital technology on SDL. Therefore, although previous studies have contributed to understanding the application of digital technology in education, there is still a lack of meta-analyses to comprehensively study the impact of digital technology on students' SDL. To fill these gaps, the main objectives of this study are to investigate the impact of digital technology on students' SDL and explore which variables moderate the effects of digital technology on students' SDL. This study aims to provide guidance and references for educators, teachers, researchers, and technology developers in their practices and research on using digital technology to support SDL. Specifically, the study proposes the following two questions:

RQ1: What is the overall effect of digital technology on students' SDL?

RQ2: What are the moderating variables that influence the effectiveness of digital technology on students' SDL?

3 METHOD

This study employs a meta-analysis approach to discuss the impact of digital technology on students' SDL, and adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. We utilized the Comprehensive Meta Analysis v.3 software for conducting the meta-analysis and adopted the Hedges' g value to calculate the effect size. According to Cohen's Hedges' g standard, 0.2 represents a small effect size, 0.5 indicates a moderate effect size, and 0.8 signifies a large effect size(Hedges, 1981).

3.1 Data sources and search strategies

This study utilized the Web of Science, Google Scholar, Springer, and Elsevier databases as the platforms for literature retrieval. Additional searches were conducted using the "citation search" method to ensure comprehensive coverage of the literature. The search was not restricted to any specific type of literature, but was limited to the timeframe after 2011. The search terms were divided into two groups. The first group of search terms included "Generative AI", "GenAI", "generative artificial intelligence", "LLM", "large language model", "ChatGPT", "chatbot", "digital technology", "educational technology", "technology", "web-based tool", "online platform", "mobile app", and other key terms related to digital technology. The second group of search terms was specifically limited to "SDL", "Self-directed learning". During the search, keywords within each group were connected using the Boolean operator "OR", while the two groups were combined using the Boolean operator "AND".

3.2 Inclusion and exclusion criteria

The criteria for literature selection included: (1)The research addressed the impact of digital technology on SDL; (2)The included literature must be experimental or quasi-experimental designs with comparisons between an experimental group and a control group, and single-group pretest-posttest studies are not included in the scope of this study; (3)The experimental group receives teaching supported by digital technology, while the control group receives traditional teaching; (4)The data in the literature must be complete, including means, standard deviations, sample sizes, etc. The specific screening process is shown in Fig. 1.

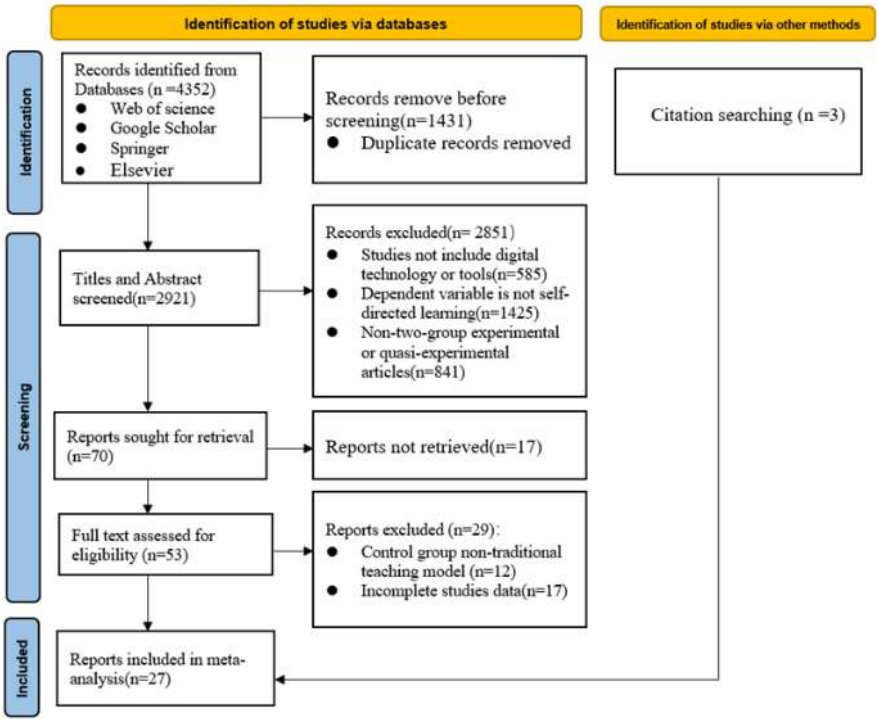

Fig. 1 Literature Search Flowchart

3.3 Coding procedures

The study not only extracted basic information from the included literature, such as article title, author(s), and year of publication, but also conducted characteristic value coding for 27 articles. The content of the characteristic value coding includes learner characteristics (education stage, subject area) and teaching characteristics (digital technology type, intervention duration, teaching size). A total of 27 articles were included in this study, among which some articles had multiple effect sizes. Therefore, there were ultimately 30 effect sizes available for meta-analysis. Two researchers independently coded all the studies separately, and the Cohen Kappa coefficient was 0.92, indicating that the coding results were valid(Cohen, 1968). After completing the coding process, the researchers discussed the disputed sections and reached a unified agreement. The specific results of the characteristic value coding are shown in TABLE 1. Initially, this study categorized digital technologies without AI involvement into two categories based on the literature included: content delivery type (i.e., digital technologies primarily for one-way knowledge transmission) and collaborative inquiry type (i.e., digital technologies that can sense user behavior and respond adaptively). In addition, AI as a transformative force(Xu & Ouyang, 2022), needs to be analyzed as an independent type of digital technology. Therefore, the study adds a

category for intelligent question-and-answer (i.e., digital technologies that rely on AI to provide dynamic responses to user inquiries and offer personalized solutions) for discussion. Therefore, the final classification of digital technology types is divided into three categories: intelligent question-and-answer, content delivery, and collaborative inquiry.

TABLE 1 Characteristic value coding

Variable		Category	Number of studies
Learner characteristics	Educational stage	1.Primary	6
		2.Secondary	4
		3.University	20
	Subject area	1.Humanities and social sciences	14
		2.Medical science	13
		3.Industrial science	3
	Technology type	1.Intelligent Question-and-Answer type	7
		2.Content delivery type	17
		3.Collaborative inquiry type	6
Teaching characteristics	Intervention duration	1. 1~3 weeks	4
		2. 4~6 weeks	8
		3. 7~9 weeks	7
		4.More than 9 weeks	11
	Teaching size	1. 1~30	3
		2. 31~60	5
		3. 61~90	12
		4. More than 90	10

3.4 Publication bias

To ensure the validity of the research conclusions, a publication bias test was conducted based on 30 effect sizes before proceeding with the meta-analysis, resulting in the funnel plot shown in Fig. 2. As shown in Fig. 2, the 30 included effect sizes are relatively evenly distributed on both sides of the funnel plot, indicating that there may be no publication bias in the study. To further confirm the presence of publication bias, the study employed the Fail-Safe Number for examination. The results showed that the Fail-Safe Number was 3478, which was far greater than the permissible limit of 5k+10 (where k is the number of effect sizes included in the analysis). In addition, the study also adopted the Egger linear regression test and the Begg rank correlation test to explore the issue of publication bias. The results showed that the p-value for the Egger linear regression test was 0.646, and the p-value for the Begg rank correlation test was 0.521, both of which were greater than 0.05. Therefore, there is no publication bias in the samples of this study, and meta-analysis can be carried out.

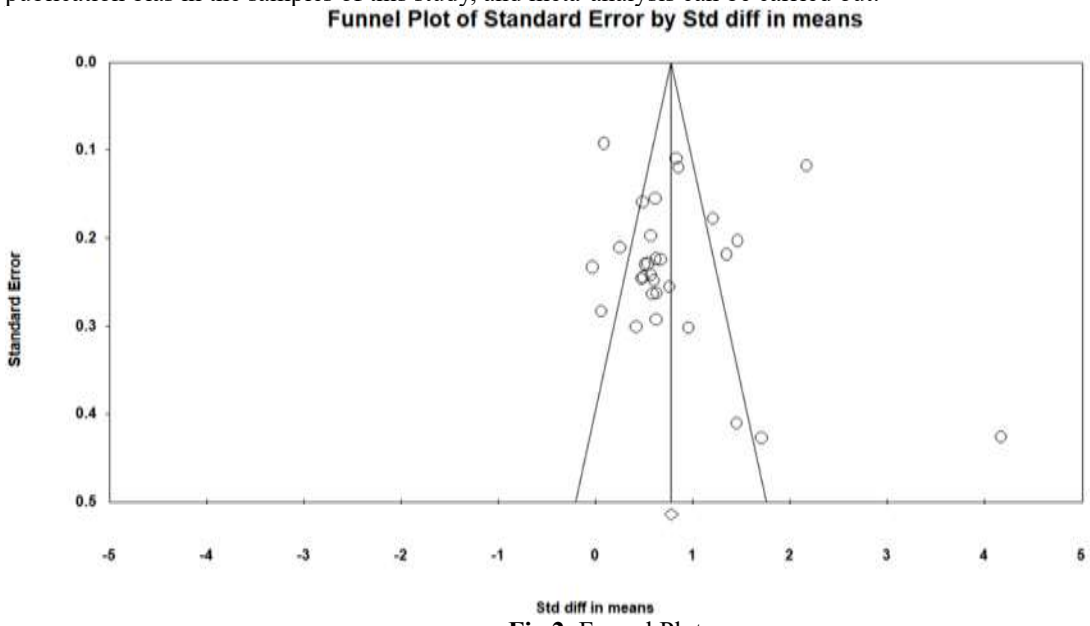

Fig 2. Funnel Plot

3.5 Heterogeneity analysis

Heterogeneity tests aim to explore the impact of individual differences on the dependent variable, with the purpose of examining whether different studies have integratability or consistency. This study utilized both fixed-effect and random-effect models to analyze the included literature. By referring to the statistical values of the Q test and I^2 test, the most appropriate model is determined to ensure the accuracy and reliability of the analysis results. The results of the heterogeneity test are shown in TABLE 2, where Q=331.249, I^2=91.249%, and p=0.000<0.1, indicating the existence of heterogeneity among the studies. Therefore, to effectively address the differences in effect sizes between samples, this study adopted a random-effects model for analysis.

TABLE 2. OVERALL EFFECT SIZE

Model	N	Hedges's g	95% confidence interval		Null test		Heterogeneity				T^2
			Lower limit	Upper limit	Z	P	Q-value	df (Q)	p	I^2	
Fixed	30	0.625	0.484	0.966	12.255	0.000	331.249	29	0.000	91.249	0.628
Random	30	0.778	0.510	0.847	6.717	0.000					

4 RESULT

4.1 The Overall Impact of Digital Technology on Self-Directed Learning

As shown in TABLE II, under the random-effect model, the overall effect size was 0.778 (95% CI: 0.510–0.847, Z = 6.717, p < 0.05), indicating that the overall impact of digital technology on students' SDL reached a moderate level. The 95% confidence interval of the random-effect model was [0.510, 0.847], which did not include 0, suggesting that the impact of digital technology on students' SDL was unlikely to be due to chance. In short, digital technology played a significant and relatively strong positive role in promoting students' SDL.

4.2 Moderator analysis findings

The study further examined the potential moderating effects of two categories of variables: learner characteristics and teaching characteristics. Learner characteristics included two variables: education stage and subject area, while teaching characteristics included three variables: technology type, intervention duration, and teaching size. Detailed data are shown in TABLE 3.

TABLE 3. Effect Size of Moderating Variables

Variables	Effect size and 95% CI				Null test		Group difference
	N	g	Lower	Upper	Z	P	
Educational stage							
1.Primary	6	0.875	0.541	1.209	5.130	0.000***	Q=0.662 P=0.718
2.Secondary	4	0.685	0.349	1.021	3.995	0.000***	
3.University	20	0.824	0.505	1.143	5.061	0.000***	
Subject area							
1.Humanities and social sciences	14	0.952	0.615	1.288	5.547	0.000***	Q=3.817 P=0.148
2.Medical science	13	0.760	0.345	1.175	3.591	0.000***	
3.Industrial science	3	0.554	0.327	0.781	4.792	0.000***	
Technology type							
1. Intelligent question-and-answer type	7	1.201	0.641	1.760	4.208	0.000***	Q=3.526 P=0.039*
2.Content delivery type	17	0.509	0.329	0.749	5.969	0.000***	
3.Collaborative inquiry type	6	0.852	0.101	1.605	2.222	0.026*	
Intervention duration							
1. 1~3 weeks	4	0.462	0.236	0.688	4.001	0.000***	Q=5.199 P=0.158
2. 4~6 weeks	8	1.055	0.248	1.863	2.561	0.000***	
3. 7~9 weeks	7	0.864	0.493	1.234	4.572	0.000***	
4.More than 9 weeks	11	0.768	0.380	1.156	3.882	0.000***	
Teaching size							

1. 1~30	3	1.574	0.994	2.154	5.322	0.000***	Q=10.631 P=0.014*
2. 31~60	5	0.897	0.486	1.308	4.278	0.000***	
3. 61~90	12	0.769	0.394	1.144	4.018	0.000***	
4. More than 90	10	0.524	0.240	0.808	3.612	0.000***	

*p <0.05,***p <0.001

4.2.1 Educational stage

To explore the impact of digital technology on students' SDL across different educational stages, this study categorized the educational stages into primary school, secondary school, and university based on the included literature. The analysis revealed that digital technology had varying degrees of positive effects on students' SDL across these three educational stages. Specifically, digital technology demonstrated strong and statistically significant positive effects on SDL among primary school students ($g = 0.875$, $p < 0.05$) and university students ($g = 0.824$, $p < 0.05$). For secondary school students, the effect was moderate but still statistically significant ($g = 0.685$, $p < 0.05$). However, the overall differences in the effects of digital technology on SDL across the three educational stages were not statistically significant ($Q = 0.662$, $p = 0.718 > 0.05$). Therefore, educational stage did not significantly moderate the impact of digital technology on students' SDL.

4.2.2 Subject area

To investigate the impact of digital technology on students' SDL across different subject areas, this study classified the included literature into three categories: humanities and social sciences, medicine, and engineering. The analysis revealed varying degrees of positive effects of digital technology on students' SDL across these subject areas. Specifically, digital technology demonstrated a strong and statistically significant positive effect on SDL in humanities and social sciences ($g = 0.952$, $p < 0.05$). In medicine ($g = 0.760$, $p < 0.05$) and engineering ($g = 0.554$, $p < 0.05$), the effects were moderate yet still statistically significant. However, the overall differences in digital technology's effects on SDL across these three subject areas were not statistically significant ($Q = 3.817$, $p = 0.148 > 0.05$). Consequently, subject area did not serve as a significant moderator of digital technology's impact on students' SDL.

4.2.3 Technology type

To examine the impact of different types of digital technology on students' SDL, this study categorized the digital technologies into three types based on the included literature: content presentation, collaborative inquiry, and intelligent question-and-answer. All three types of digital technologies demonstrated positive effects on students' SDL, though to varying degrees. Specifically, intelligent question-and-answer ($g = 1.201$, $p < 0.05$) and collaborative inquiry ($g = 0.852$, $p < 0.05$) technologies showed strong and statistically significant positive effects on students' SDL. Content presentation technology ($g = 0.509$, $p < 0.05$) exhibited a moderate yet still statistically significant positive effect. Moreover, the overall differences in the effects among these three types of digital technologies were statistically significant ($Q = 0.278$, $p = 0.039 < 0.05$). Therefore, the type of digital technology significantly moderates its impact on students' SDL.

4.2.4 Intervention duration

To examine the impact of digital technology on students' SDL across different intervention durations, this study classified the intervention periods into four categories based on the included literature: 1-3 weeks, 4-6 weeks, 7-9 weeks, and more than 9 weeks. Digital technology demonstrated varying degrees of positive effects on students' SDL across these intervention periods. The analysis revealed statistically significant positive effects with varying effect sizes: strong effects were observed for interventions lasting 4-6 weeks ($g=1.005$, $p<0.05$) and 7-9 weeks ($g=0.864$, $p<0.05$), while moderate yet significant effects were found for shorter (1-3 weeks; $g=0.462$, $p<0.05$) and longer durations (more than 9 weeks; $g=0.768$, $p<0.05$). However, the overall analysis showed no statistically significant differences in digital technology's effects on students' SDL across different intervention durations ($Q=5.199$, $p>0.05$). Therefore, intervention duration did not significantly moderate the impact of digital technology on students' SDL.

4.2.5 Teaching size

To investigate the impact of digital technology on students' SDL under different teaching sizes, this study categorized teaching sizes into four groups based on the included literature: 1-30 participants, 31-60 participants, 61-90 participants, and more than 90 participants. Digital technology had a positive impact of varying degrees on students' SDL across these three teaching sizes. Specifically, in teaching sizes of 1-30 participants ($g=1.574$, $p<0.05$) and 31-60 participants ($g=0.897$, $p<0.05$), digital technology had a high significant positive impact on students' SDL. In teaching size of 61-90 participants ($g=0.769$, $p<0.05$) and more than 90 participants ($g=0.524$, $p<0.05$), digital technology had a moderate significant positive impact on students' SDL. Overall, there were significant differences in the impact of digital technology on students' SDL across different teaching scales

(Q=10.631, p=0.014<0.05). Therefore, teaching size can significantly moderate the impact of digital technology on students' SDL.

5 DISCUSSION

To address the first research question, our meta-analysis included 27 studies on digital technology supporting students' SDL, encompassing a total of 30 effect sizes. The results indicated that digital technology has a moderate positive impact on students' SDL, suggesting significant potential for enhancing students' SDL through digital technology.

Possible reasons include: Firstly, digital technology provides students with abundant learning resources through the internet, databases, and other means. Students can independently choose learning content and adjust their learning pace according to their interests or needs, breaking through the temporal and spatial constraints of traditional classrooms. As relevant research has pointed out, the richness of online resources enables learners to actively construct knowledge networks rather than passively accept fixed course content(Hmelo-Silver et al., 2007). The support of digital technology for student learning resources meets the core elements of SDL, namely self-setting learning goals and autonomous selection of resources(Knowles, 1975), thereby stimulating students' interest and initiative in learning, which is a significant driving force for SDL. Secondly, powerful digital technology offers convenience for teachers to cultivate students' SDL. Teachers can use digital technology (e.g., teaching management systems, online testing tools) to accurately assess and fully understand students' learning situations, so as to decide whether to take intervention measures to assist students' SDL and timely adjust teaching plans and optimize teaching models(Walan, 2020). Moreover, digital technology can help teachers create an SDL environment suitable for students' characteristics (e.g., immersive learning environments), optimizing students' learning experiences and enabling learners to engage in more interesting and participatory SDL experiences. In addition, the diverse tools and platforms of digital technology have promoted students' SDL. For example, intelligent learning applications can provide personalized learning suggestions and feedback based on students' learning behaviors and data, as well as functions such as simulated tests and practice exercises to help students consolidate knowledge and improve skills. Learning management systems can assist students in organizing and managing their learning courses, tasks, and progress. Students can use these systems to organize learning content and resources, conduct efficient information processing, and record their learning outcomes for self-assessment. The diverse digital tools provide effective support for students, enabling them to better grasp the direction of learning, improve self-management, and enhance SDL.

Similarly, GenAI supports students through interactive dialogue capabilities, providing real-time answers and feedback that allow learners to progress at their preferred pace. GenAI offers broad accessibility across platforms, enabling students to explore and utilize open educational resources flexibly. By tailoring content recommendations to individual needs, GenAI further personalizes the learning experience. These integrated features enhance students' autonomy and ability to manage their own learning, thereby strengthening their capacity for self-directed learning.

The research results affirm the application value of digital technology in cultivating students' SDL. Therefore, the education sector needs more investment and effort to promote the application of digital technology in SDL cultivation. We should not overly worry about the negative impacts of digital technology, particularly GenAI, but must encourage teachers and educators to dare to utilize, reasonably utilize, and innovatively utilize digital technology to support students' SDL.

To address the second research question, this study further explored potential moderating variables, which were divided into student characteristics (educational stage, subject area) and teaching characteristics (digital technology type, intervention duration, teaching size). Among these, digital technology type and teaching size significantly moderated the impact of digital technology on students' SDL.

Regarding educational stage, digital technology showed better effects on SDL for primary and university students compared to secondary students. Primary students are in a critical period of cognitive development, with greater plasticity in their SDL development and predominantly concrete thinking(Hartshorne & Germine, 2015). Digital technology can transform abstract knowledge into more intuitive visual representations, which aligns with their cognitive characteristics and attracts their attention. Additionally, primary students easily gain a sense of accomplishment and confidence from using digital educational games, thereby increasing their learning engagement. This explains the better SDL outcomes observed in Primary students. Consistent with the findings of Han et al. (2022), university students possess higher digital literacy and greater access to digital devices, along with prior experience and proficiency in using digital technology(Garzón & Acevedo, 2019), enabling them to fully leverage these tools for SDL.

In contrast, secondary students face several challenges. First, in the regions studied, most secondary students experience significant academic pressure due to transition to higher education, which may lead them to prioritize rote learning over SDL skill development(Bound et al., 2009). Second, secondary students are in the developmental stage of adolescence. Secondary students exhibit greater emotional volatility and susceptibility to external distractions(Demkowicz et al., 2024), resulting in insufficient self-management when using digital technology for learning and difficulty adhering to study plans. Furthermore, current research on SDL cultivation primarily focuses on university students, with limited attention to secondary students. Future research needs to emphasize the development of students' SDL at the secondary stage. This may require collaborative efforts from society, families, and schools to provide additional support and guidance for cultivating SDL in secondary students.

Regarding subject area, digital technology showed better effects on SDL for students in the humanities and social sciences compared to those in medicine and engineering. This contrasts with previous findings, such as Bašić et al. (2023), who reported higher student interest and acceptance of digital technology when applied to natural sciences. The discrepancy may stem from the nature of learning content in different fields. Humanities and social sciences often emphasize the analysis and understanding of texts, history, culture, and social phenomena(Marcone, 2022), which require considering the diversity and complexity of real-world contexts. Digital technology can effectively create authentic, complex scenarios for discussion and exploration, facilitating SDL in these disciplines.

In contrast, medicine and engineering prioritize standardized experimental processes and specialized technical skills(Barlösius, 2019). These fields rely more on practical experience and professional guidance, posing higher demands for equipment and technical support compared to humanities and social sciences. Consequently, the application of digital technology to SDL in these areas may be more limited. Overall, digital technology demonstrates significant positive effects on SDL across disciplines. This insight suggests that educators can leverage digital tools for interdisciplinary teaching to cultivate SDL. Additionally, there is a need to explore and select digital technologies tailored to the specific needs of different academic fields to better support students' SDL.

Regarding digital Technology Type, this study found that different types of digital technology have a significant positive impact on students' SDL. While some research suggests that the most common challenge in using digital technology in classrooms is students' lack of skills in using it rather than questions about which technology to use(Seenivasan, 2024), our results underscore the importance of providing targeted digital technologies for SDL.

Specifically, intelligent question-and-answer technologies and collaborative inquiry technologies outperform content-delivery technologies in promoting SDL. As an emerging form of digital technology, intelligent question-and-answer tools leverage AI to offer personalized learning content and interactive experiences. These technologies significantly enhance learning efficiency, motivation, and knowledge construction(Ng et al., 2023), while also transforming teaching strategies and sparking greater interest and participation(Huang et al., 2023), thereby intelligent question-and-answer technologies can foster SDL. Collaborative inquiry technologies create immersive environments that enable deep collaboration, knowledge co-creation, and improved engagement, while cultivating problem-solving skills. In contrast, content-delivery technologies, which primarily provide one-way information transmission, lack personalization, flexibility, and practicality. They may fail to meet diverse learning needs, limiting their effectiveness in supporting SDL.

This finding highlights the critical role of educators in selecting appropriate digital technologies. When designing instructional activities, educators should prioritize aligning technology types with teaching objectives, embrace artificial intelligence applications in education, and emphasize designs that integrate theory and practice.

Regarding intervention duration, SDL outcomes were better under 4-6 weeks and 7-9 weeks of intervention compared to 1-3 weeks or more than 9 weeks. A moderate intervention period allows students to fully understand and familiarize themselves with the digital technology while maintaining high learning efficiency. During this time, teachers are more likely to invest greater resources and effort into the teaching process(Sung et al., 2016).

In contrast, shorter interventions (e.g., 1-3 weeks) may leave students insufficiently familiar with the technology. Students often need time to adapt and effectively integrate new tools into their learning practices(Ganesh et al., 2022). Additionally, SDL, as a complex competency, may not improve significantly in the short term. Longer interventions (e.g., over 9 weeks) risk diminishing student engagement due to reduced novelty(Chauhan, 2017), increased cognitive load, and greater challenges for teachers to control extraneous variables(Ganesh et al., 2022). This suggests that teachers should ensure students use digital technology adequately within a reasonable

timeframe, avoiding both brief or excessive use. Overall, since intervention duration does not significantly moderate the impact of digital technology on SDL, teachers can flexibly arrange teaching schedules based on practical instructional needs.

Regarding teaching size, interventions in 1-30 and 31-60 student groups outperformed those in 61-90 and over 90 student groups. Sun and Zhou (2024) also concluded that moderate-sized classes can leverage the advantages of digital technology more effectively. In smaller or medium-sized classes, teachers can better integrate digital tools for targeted guidance, as they have more time and energy to manage the class and control learning pace(Bucea-Manea-Țoniș et al., 2022). In contrast, large-scale teaching often leaves teachers unable to adequately monitor each student's SDL, leading to insufficient supervision and personalized support. Students may fail to fully utilize digital technology for SDL(Hobert et al., 2023), and the massive volume of learning data could also cause technical errors. In general, the teaching size is determined more by the actual teaching situation and is constrained by real conditions, making it difficult to adjust artificially. Therefore, educators should prioritize innovative digital teaching methods and enhance their instructional management skills when facing large-scale classes to foster SDL. At the same time, technologists must continuously optimize the data capacity of digital tools to address scalability challenges.

6 CONCLUSIONS

This study investigated the effectiveness of digital technology in enhancing students' SDL, analyzing 30 effect sizes from 27 studies involving 3,711 participants across diverse groups. Meta-analysis results indicate that digital technology has a moderately significant positive impact on SDL. Among moderating variables such as educational stage, subject area, digital technology type, intervention duration, and teaching size, significant differences were observed in digital technology type and teaching size. Specifically, the use of digital technologies and interventions in 1-30 student classes yielded the greatest improvements in SDL.

This reveals us that: firstly, teachers with the necessary knowledge and skills can venture to attempt the use of digital technology in SDL development, as this study has demonstrated the positive effects of digital technology in students' SDL. Second, AI, as a revolutionary force(Xu & Ouyang, 2022), has likewise brought convenience to SDL. Teachers must seize the opportunities brought by AI and continue to learn and study the application of AI in teaching. In addition to this, it is also important to focus on the impact of teaching scale and try to promote small class sizes in SDL training to optimize the effect of digital technology. Finally, although the analysis of moderating variables showed no significant moderating effect of educational stage, subject area, and intervention duration, teachers should also use digital technologies under appropriate conditions. Relatively speaking, digital technologies demonstrate less effective application among secondary students. Teachers, families, and the community need to focus on providing appropriate guidance to secondary students to help them make full use of digital technologies for SDL. Digital technology has different effects on students' SDL under different subject areas, and it is necessary for researchers to continuously develop and improve digital technology to suit the needs of learning in different subjects. Teachers also need to rationalize the amount of time students use digital technology to avoid using it for too short or too long. This study confirms the positive role and potential of digital technology in students' SDL development. This study provides theoretical guidance on how to optimize digital technology teaching and SDL activities, as well as a practical basis for digital technology educational applications and related policy development.

However, there are some limitations to this study. First, the meta-analysis included a limited amount of literature, which may have led to an incomplete view of this study. Future research should expand the databases searched to broaden the scope of literature retrieval, thereby accessing a wider range of data sources and enhancing the scientific rigor of the study. Second, the moderating variables chosen for the study were not comprehensive. For example, gender and geography may also moderate the impact of digital technology on students' SDL. Future research can continue to explore possible moderating variables in depth to draw more comprehensive findings. In addition, this study examines SDL as a competency. However it is not possible to neglect to explore the impact of digital technologies on SDL from a process viewpoint. Finally, the long-term validity of the findings of this study may be limited due to the rapid development of digital technology. Therefore, more relevant research is needed to provide a sustained focus on emerging digital technologies. For example, AI technology is rapidly evolving, and due to the limited amount of relevant literature that could be included, the study failed to focus on the effects of AI on students' SDL, and subsequent research needs to be focused on and refined.

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