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Collaborative Digital Learning-Augmented Reality Instructional Design to Improve Digital Literacy in Science Education at Primary Schools

Didit Yulian Kasdriyanto,^{*,1} Ribut Prastiwi Sriwijayanti,¹ Tamam Asrori,¹ Ludfi Arya Wardana,² and Win Phyu Thwe, PhD³

¹Elementary School Teacher Education Department, Universitas Panca Marga, Indonesia

²Computer Science Department, Universitas Panca Marga, Indonesia

³Pyay Education Degree College, Myanmar

*Corresponding author: didityulian@upm.ac.id

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Abstract

This study aimed to develop a valid, practical, and effective Collaborative Digital Learning-Augmented Reality (CoDL-AR) instructional design to improve digital literacy in primary science education. The study employed a research and development (R&D) method adapted from the Dick and Carey model, involving preliminary analysis, instructional design, product development, expert validation, limited and extensive trials, and effectiveness testing. The participants consisted of 192 fifth-grade students from four elementary schools in Probolinggo Regency, Indonesia. Data were collected using validation sheets, observation sheets, practicality questionnaires, and digital literacy tests covering seven indicators: digital device operation, information access, information evaluation, digital communication and collaboration, digital creativity, digital ethics, and digital security. The results showed that the CoDL-AR instructional design achieved highly valid categories in content and construct validation. The findings demonstrated that the instructional model exhibited a high degree of practicality and satisfactory reliability across all instructional phases. Furthermore, the effectiveness analysis revealed significant improvements in students' digital literacy, supported by medium to high N-Gain scores and significant paired-samples *t*-test results ($p < 0.05$). Therefore, the CoDL-AR instructional design effectively enhances digital literacy and supports meaningful science learning experiences in primary education.

Keywords: Augmented Reality; Collaborative Learning; Digital Literacy; Instructional Design; Primary Science Education.

1. Introduction

The spread of digital technology internationally has been enhanced by the speed of globalization, which has brought great change in educational practices all over the world. The use of technology in primary education is becoming prominent due to the availability of digital learning materials such

as computers, laptops, mobile phones, and interactive multimedia materials ([1]; [2]). In Indonesia, this transformation is congruent with the priorities of the Directorate General of Research and Development and the Presidential agenda *Asta Cita* that aims at improving education, science, technology, and digitalization. Moreover, it promotes Sustainable Development Goal (SDG) 4 on quality education and SDG 9 on innovation and technological infrastructure. In particular, SDG indicator 4.4 underlines that it is necessary to develop digital skills that can be used in lifelong learning, and 9.5 urges the adoption of innovation by integrating technology into learning. Digital literacy has thus become a key competence that must be nurtured during the primary schooling stage to equip learners to meet the challenges of the digital age ([3]; [4]).

Digital literacy is not just the skill to use the work of technology. It encompasses the skills of critically evaluating information, understanding digital ethics and security, collaborative communication, and knowledge building using digital platforms ([5]; [6]). However, despite the increasing popularity of technology-based learning media in primary schools in Indonesia, such as Probolinggo Regency, East Java, technology learning media remains teacher-based and content-based. Current technologies like learning videos and interactive multimedia are often used as an informational delivery tool, instead of as a learning environment. Students will, therefore, not be active users of technology, but rather passive users who can construct knowledge constructively and critically. This can potentially cripple the advancement of digital literacy among learners, particularly in those subjects dealing with digital communication, teamwork, and information analysis.

Previous research has demonstrated that technology-based instructional innovations can contribute positively to learning effectiveness, student motivation, and learner engagement ([7]; [8]). Among emerging educational technologies, Augmented Reality (AR) has attracted considerable scholarly attention because of its capacity to superimpose virtual objects onto the physical environment in real time, thereby creating immersive and interactive learning experiences ([9]; [10]). By integrating digital content with the learners' immediate physical surroundings, AR can facilitate the representation of abstract scientific concepts through multimodal forms of learning, including visual, auditory, and kinaesthetic representations. Such capabilities may enhance students' conceptual understanding by enabling them to interact with and visualize scientific phenomena in more concrete and meaningful ways. Furthermore, previous studies have reported that the integration of AR into educational settings can positively influence students' interest, motivation, and engagement in the learning process ([11]; [12]). In addition to these general educational benefits, AR has been applied in contextualized science-learning applications, including fruit-recognition applications and interactive storytelling applications designed for children ([13]; [14]). These applications demonstrate the potential of AR to connect digital representations with authentic learning contexts and provide more engaging and contextually meaningful experiences in science education.

At the same time, collaborative learning is an effective pedagogical approach that encourages interaction, critical dialogue, exchange of knowledge, and problem-solving among students ([15]). Online learning groups have the potential to enhance both higher-level thinking and communication and encourage active student engagement. However, the current literature inclines to research collaborative learning and AR independently. Other previous studies were primarily focused on the creation of instructional media such as multiplication wheel media, quiz flashcards, pop-up books, smart boards, and interactive ([16]; [17]; [18]). Although these studies proved the alterations of learning interest and reading motivation, they rarely addressed the digital literacy of students in a combined manner.

A further research gap can be identified through a bibliometric analysis conducted using VOSviewer on Scopus-indexed publications published between 2015 and 2025, with "collaborative learning" and "augmented reality" used as the primary search keywords. The resulting visualization indicates relatively limited linkages among collaborative learning, mobile augmented reality, multimedia, and

digital literacy, as reflected in the comparatively low network density among these thematic clusters. This pattern suggests that the intersection of collaborative digital learning, augmented reality, and digital literacy remains insufficiently explored, particularly within the context of primary science education. Although the existing literature has increasingly examined the educational applications of AR, much of this research has concentrated on outcomes such as student motivation, interaction, engagement, and conceptual understanding. In contrast, comparatively limited attention has been given to the potential of AR-supported collaborative learning to systematically develop students' digital literacy skills. Therefore, further research is warranted to investigate how the integration of collaborative learning and AR can be strategically designed to foster digital literacy while simultaneously supporting meaningful science learning among primary school students.

Therefore, this study suggests the creation of a Collaborative Digital Learning–Augmented Reality (CoDL-AR) teaching model to enhance digital literacy in primary science education. What makes the research original is that the notions of collaboration in digital learning are unified with the application of AR technology to the issue of a systematic approach to instruction design and the development of digital literacy skills in students. In contrast to former works which mainly focused on interest in learning or attractiveness of media, the CoDL-AR design focuses on students having skills to work digitally, assess information critically, communicate ethically, and be creative in using technology when learning science activities. Moreover, the study contributes to addressing a gap in the theoretical background of collaborative pedagogy, AR technology, and digital literacy development in primary education settings. Practically, the result is a proven instructional design book and AR use guidelines, which will most likely provide educators with a new framework for introducing technology-enhanced learning of science in elementary schools.

As has been shown, the digital literacy of elementary students is not even: in Indonesian science education, the level of using digital tools and creating digital materials was rather low; at the same time, the level of information processing and collaboration was average ([19]). The other outcomes possess greater access skills in contrast to higher-order skills such as information analysis and development of digital content ([20]). Even though AR has the potential to increase the digital literacy and collaborative communication of pupils, and cooperative learning with the support of AR could be used to increase science literacy ([21]) prior research seldom combines these aspects in a systematic design aimed at increasing digital literacy in science. CoDL-AR bridges this void by integrating collaborative learning, AR exploration, and digital-literacy-driven activities.

2. Methods

This study employed a research and development (R&D) design to develop a valid, practical, and effective Collaborative Digital Learning–Augmented Reality (CoDL-AR) instructional model aimed at enhancing digital literacy in primary science education. The development process was guided by the instructional development framework proposed in [22], which comprises seven systematic stages: (1) preliminary study and needs analysis, involving the identification of students' digital literacy needs and the characteristics of the existing learning context; (2) instructional planning, including the formulation of learning objectives, digital literacy indicators, instructional strategies, and assessment procedures; (3) CoDL-AR product development, encompassing the development of the instructional design guide, science-learning activities, and guidelines for AR integration and use; (4) expert validation, focusing on instructional relevance, pedagogical integration, AR usability, digital literacy development, language clarity, and instructional feasibility; (5) limited-scale trial, conducted to assess the initial practicality, usability, and applicability of the developed model; (6) large-scale implementation and effectiveness testing, involving classroom implementation and the measurement of students' digital literacy through pretest and post-test assessments; and (7) final revision and dissemination, undertaken on the basis of empirical findings, implementation feedback, and

expert evaluations. Through these iterative stages, the CoDL-AR instructional model was progressively refined to ensure its theoretical validity, practical feasibility, and effectiveness in supporting digital literacy development in primary science education.

The participants were 192 fifth-grade students from four primary schools in Probolinggo Regency, East Java, Indonesia. The schools were selected using criterion-based purposive sampling, based on their classification as high-, medium-, or low-performing schools according to the empirical criterion used. This sampling technique worked well in representing the learning environment and access to technology amongst students. The participant distribution was [School 1: $n = 50$; School 2: $n = 42$; School 3: $n = 52$; School 4: $n = 48$]. Science learning material that was involved with the solar system was the focus of the implementation.

The data collection was based on the validation sheets, observation sheets, practicality questionnaires, and digital literacy tests. The digital literacy tool was developed based on seven indicators, namely: (1) digital device operation, (2) information access and navigation, (3) digital information evaluation, (4) digital communication and collaboration, (5) digital creativity, (6) digital ethics, and (7) digital security ([23]). Data were collected using expert-validation sheets, classroom-observation sheets, practicality questionnaires, and digital-literacy tests. The digital-literacy instrument assessed seven dimensions: digital-device operation, information access and navigation, digital-information evaluation, digital communication and collaboration, digital creativity, digital ethics, and digital security.

The CoDL-AR instructional design was tested in terms of expert judgment that was based on experts in science education, instructional design experts, and elementary education practitioners to assess content and construct validity. The validation variables included: (1) instructional relevance, (2) implementation of principles of collaborative learning, (3) AR usability, (4) digital literacy appropriateness, (5) language understandability, and (6) instructional feasibility. A score range of $1.00 \leq P \leq 4.00$ was used to ascertain the level of feasibility ([24]). Classroom observations and teacher responses were used to determine the practicality of the instructional design by using the percentage agreement criterion of $> 75\%$ ([25]).

The digital literacy test tool had pretest and post-test questions that were developed based on the seven dimensions of digital literacy. The validity of the items with the criterion of $\text{Sig.} < 0.05$ was analyzed using Pearson Product Moment correlation. The reliability of the instrument was analyzed using Cronbach's Alpha coefficient, with the criterion $\alpha > 0.60$ indicating acceptable reliability.

Table 1. Results of the digital literacy test validity

Pretest				Posttest			
Item	Provisions	Sig. Value	Description	Item	Provisions	Sig. Value	Description
P1	Sig. < 0.05	< 0.001	Valid	Q1	Sig. < 0.05	< 0.001	Valid
P2	Sig. < 0.05	0.003	Valid	Q2	Sig. < 0.05	< 0.001	Valid
P3	Sig. < 0.05	0.027	Valid	Q3	Sig. < 0.05	0.009	Valid
P4	Sig. < 0.05	0.027	Valid	Q4	Sig. < 0.05	0.008	Valid
P5	Sig. < 0.05	< 0.001	Valid	Q5	Sig. < 0.05	0.004	Valid
P6	Sig. < 0.05	< 0.001	Valid	Q6	Sig. < 0.05	0.018	Valid
P7	Sig. < 0.05	0.012	Valid	Q7	Sig. < 0.05	0.011	Valid

Table 2. Results of the reliability test for digital literacy questions

Pretest			Posttest		
Cronbach's Alpha	Provisions	Description	Cronbach's Alpha	Provisions	Description
0.721	Alpha > 0.60	Reliable	0.784	Alpha > 0.60	Reliable

The validity analysis demonstrated that all items included in the pretest and posttest instruments met the established validity criteria, with significance values below 0.05. These findings indicate that each item was statistically valid for measuring the intended dimensions of students' digital literacy. Accordingly, the items were considered sufficiently representative of the constructs examined in this study and appropriate for subsequent data collection and analysis.

Furthermore, the reliability analysis showed that both the pretest and posttest instruments yielded Cronbach's alpha coefficients above the minimum threshold of 0.60, indicating satisfactory internal consistency among the items. This result suggests that the instruments provided sufficiently consistent measurements of students' digital literacy. Therefore, the digital literacy assessment instrument was considered reliable for evaluating changes in students' digital literacy following the implementation of the CoDL-AR instructional design.

To further evaluate the effectiveness of the CoDL-AR instructional design, N-Gain analysis and a paired-samples *t*-test were employed. These statistical procedures were selected because the same students participated in both the pretest and posttest assessments of digital literacy ([26]). The N-Gain analysis was used to determine the magnitude of improvement in students' digital literacy, whereas the paired-samples *t*-test was applied to examine whether the difference between pretest and post-test scores was statistically significant. Taken together, these analyses provided complementary evidence regarding the extent to which the CoDL-AR instructional design contributed to the improvement of digital literacy among primary school students in science learning.

3. Results and Discussion

3.1 Results

3.1.1 Development

Development of products in the form of CoDL-AR instructional design to enhance digital literacy in science education at the primary level. This product is an improvement of the CoDL-AR phases that are in Table 3

Table 3. Phase CoDL-AR learning design and activity

Phase	Activity	Indicators of Digital Literacy
Problem Orientation	a. Students observe science phenomena through AR visualization related to the solar system. b. The teacher stimulates students using contextual digital questions and multimedia content.	Information access and navigation, Digital device operation
Collaborative Exploration	a. Students work collaboratively in groups to explore AR-based learning materials. b. The teacher facilitates digital interaction and group discussion.	Digital communication and collaboration, Digital device operation
Digital Information Analysis	a. Students identify, compare, and evaluate digital information obtained from AR applications and online sources. b. The teacher guides students in distinguishing valid and invalid information.	Digital information evaluation, Information access and navigation

Phase	Activity	Indicators of Digital Literacy
AR-Based Investigation	a. Students conduct simple science investigations using AR media to observe planetary characteristics and movements. b. The teacher assists students in operating AR applications effectively.	Digital creativity, Digital device operation
Collaborative Knowledge Construction	a. Students discuss investigation results and construct group conclusions using digital platforms. b. The teacher encourages active participation and collaborative problem-solving.	Digital communication and collaboration, Digital ethics
Digital Content Creation	a. Students create digital products such as posters, presentations, or short videos related to the solar system. b. The teacher provides feedback on students' creativity and digital presentation quality.	Digital creativity, Information access and navigation
Reflection and Digital Ethics	a. Students reflect on their learning experiences and responsible use of technology during collaborative activities. b. The teacher reinforces ethical and safe digital behavior.	Digital ethics, Digital security
Presentation and Evaluation	a. Students present their collaborative digital projects using AR-supported media. b. The teacher evaluates students' digital literacy performance using assessment rubrics and provides feedback.	Digital communication and collaboration, Digital creativity, Digital information evaluation

Table 3 shows how each CoDL-AR phase is aligned with the desired digital literacy indicators. It begins with the working of the device and access to information in the orientation of problems and moves to digital collaboration and communication in collaborative exploration. The students then process the information, ask AR-based questions, collaborate to develop knowledge, create digital resources, and apply digital ethics and security. By so doing, digital literacy is built into the sequence of learning and is not regarded as a distinct learning outcome. The CoDL-AR design is an important contribution to this phase-indicator alignment.

3.1.2 Validity

CoDL-AR instructional design was pilot-tested with three professionals to determine content and construct validity and to determine the feasibility, consistency, and suitability of the instructional model to improve the level of digital literacy in primary science classrooms. An expert validation process was carried out to get suggestions and revisions on how the instructional product could be better prior to its implementation in classes. Table 4 shows the results of the content validation.

Table 4. Results of Content Validity Assessment of the CoDL-AR Instructional Design

Assessment Aspect	Validator 1	Validator 2	Validator 3
Analysis of CoDL-AR Development Needs	4	3	4
Integration of Collaborative Learning	4	4	3
AR-Based Instructional Framework	3	4	4
Digital Literacy Integration	4	3	4
Language and Instructional Clarity	3	4	3
Mean	3.6	3.6	3.6
Category	Highly Valid	Highly Valid	Highly Valid

The results of the content validity show that all the validators rated CoDL-AR instructional design as highly valid; the mean score is 3.6. The positive scores confirm that the instructional design reflects the concepts of collaborative learning, AR technology, and digital literacy skills in primary science learning in a satisfactory manner.

Table 5. Results of the CoDL-AR Instructional Design Construct Validity Assessment

Assessment Aspect	Validator 1	Validator 2	Validator 3
Consistency of CoDL-AR Syntax	4	4	4
Consistency between Theory and Empirical Support	4	3	4
Clarity of Instructional Procedures	3	4	3
Mean	3.67	3.67	3.67
Category	Highly Valid	Highly Valid	Highly Valid

The construct validity results indicate that the Collaborative Digital Learning–Augmented Reality (CoDL-AR) instructional design demonstrates strong theoretical coherence and empirical support. The validators assigned a mean score of 3.7 to the instructional design, indicating a high level of validity. Furthermore, the experts agreed that the instructional stages were systematically structured and theoretically grounded in collaborative learning theory, digital literacy development, and AR-based instructional practices. These findings suggest that the CoDL-AR instructional design provides a coherent pedagogical framework in which collaborative learning activities, digital literacy competencies, and augmented reality technologies are integrated to support science learning at the primary school level.

3.1.3 Practicality

The CoDL-AR instructional design underwent testing regarding feasibility through conducting limited and extensive classroom testing in four elementary schools. The implementation observations were based on eight instructional stages, classroom setting, and time management. The results of the implementation are shown in Table 6.

Table 6. Implementation of the CoDL-AR Instructional Design

School	Implementation								Classroom Atmosphere	Time Management
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8		
Limited Trial at SDN Sumbertaman 2	3.7	3.8	3.6	3.7	3.5	3.8	3.6	3.9	3.7	3.2
Extensive Trial at SDN Sumberwetan 1	3.6	3.7	3.5	3.8	3.6	3.7	3.5	3.8	3.6	3.3
Extensive Trial at SDN Kedungdalem 2	3.8	3.9	3.7	3.8	3.7	3.8	3.6	4.0	3.8	3.6
Extensive Trial at SDN Curahan Sawo	4.0	4.0	3.9	4.0	3.9	4.0	3.8	4.0	3.9	3.8
Mean	3.8	3.9	3.7	3.8	3.7	3.8	3.6	3.9	3.8	3.5

School	Implementation								Classroom Atmosphere	Time Management
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8		
Implementation Percentage (%)	92.2	95.1	91.4	93.7	92.0	94.0	90.2	96.5	93.1	87.5
Category	High	High	High	High	High	High	High	High	High	High

The results of implementation show that CoDL-AR instructional design proved to be feasible and practical to be used in the classroom. All phases of implementation scored high (3.6-3.9). The highest implementation score was achieved at Phase 8 (Presentation and Evaluation), which means that students were involved in the process of a presentation of collaborative digital products using AR technology.

3.1.4 Effectiveness

Pretest and post-test scores and N-Gain analysis of data on digital literacy skills of students were the basis of CoDL-AR instructional design testing. Table 7 provides the results of the effectiveness analysis.

Table 7. Average Pre-test, Post-test, and N-Gain Scores for CoDL-AR Instructional Design

Achievements	Limited Trial at SDN Sumbertaman 2				Extensive Trial at SDN Sumberwetan 1				Extensive Trial at SDN Kedungdalem 2				Extensive Trial at SDN Curahsawo			
	Class A		Class B		Class A		Class B		Class A		Class B		Class A		Class B	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Lowest Score	52	78	45	70	48	82	44	68	50	84	42	70	55	86	46	72
Highest Score	85	98	78	92	88	100	80	90	90	100	82	92	92	100	84	94
Average Score	58.24	84.56	53.72	80.12	60.35	88.40	54.28	78.56	62.48	90.24	49.36	76.80	64.12	92.16	50.24	79.44
Total of Students	25	25	25	25	22	22	20	20	25	25	27	27	25	25	23	23
Average N-Gain																
	0.63		0.57		0.71		0.53		0.74		0.54		0.78		0.58	
Category	Medium		Medium		High		Medium		High		Medium		High		Medium	

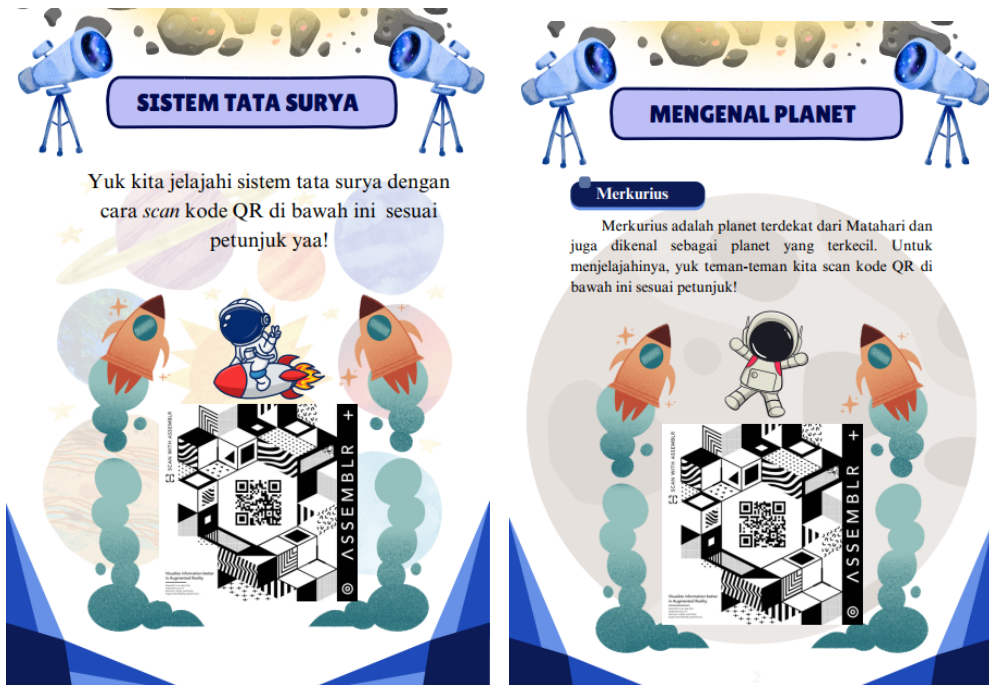


Figure 1. AR-supported solar-system learning activity within the CoDL-AR instructional design

Figure 1. CoDL-AR learning design: AR-based solar-system learning environment. The figure illustrates the utilization of augmented reality in enabling students to learn about the solar system as part of the CoDL-AR process. AR visualization enables learners to be collaborative and to discuss online pictures of planetary bodies. Therefore, the figure illustrates that AR is an incorporated part of the CoDL-AR instructional design as opposed to an independent learning medium.

3.2 Discussion

The findings suggest that the CoDL-AR instructional design can enhance students' digital literacy by integrating augmented reality (AR) into collaborative science-learning activities rather than employing AR merely as a visualization tool. Through this integrated approach, students engage in a range of digital literacy practices, including accessing and evaluating information, communicating and collaborating through digital technologies, creating digital content, and applying ethical principles and safety considerations in digital environments. These activities position students as active participants in the processes of scientific inquiry, information evaluation, and collaborative knowledge construction. Furthermore, the findings extend previous research on AR-supported learning, which has predominantly focused on student motivation, engagement, and conceptual understanding. By contrast, the CoDL-AR instructional design conceptualizes AR as a multidimensional learning environment that facilitates inquiry-based exploration, information processing, digital collaboration, and the development of broader digital literacy competencies. Thus, the model offers a pedagogical framework for integrating AR technology with collaborative science learning to support the development of digital competencies among primary school students ([27]; [28]; [29]).

The stronger contribution may be explained by the integration of technological affordances with explicit digital-literacy tasks and collaborative scaffolding, which provided repeated opportunities to practice multiple literacy dimensions. This interpretation is consistent with evidence that collabo-

rative online learning can strengthen interaction and participation ([30]; [31]), while extending it by demonstrating how AR-supported collaboration can simultaneously address operational, evaluative, communicative, creative, ethical, and security dimensions of digital literacy. The high implementation reliability further supports the consistency of this instructional approach ([25]). These findings are similar to previous research that states that a collaborative online learning environment increases interaction and involvement in classrooms ([32]; [11]; [33]; [34]).

The effectiveness analysis reveals that the digital literacy of the students has been enhanced significantly if the CoDL-AR instructional design is implemented. Most of the experimental classes scored high in N-Gain scores, particularly Class A at SDN Curahsawo, where the N-Gain measure was 0.78. These results indicate that the AR-based collaborative learning was capable of improving the skills of the students related to the use of digital tools, analysis of information, online collaboration, and creation of digital products. Findings are consistent with previous studies that emphasize the idea that collaborative learning systems based on AR have a positive impact on digital activity and advanced learning skills ([35]; [12]; [29]; [36]).

The statistical assumption test was done through the Shapiro-Wilk test, which was used to test whether the data distribution was within the parameters or not. The significance values of all data were above 0.05, which means that the data were normally distributed. Hence, to compare pretest and posttest scores, paired sample *t*-tests were performed.

The paired sample *t*-test results revealed statistically significant ($p < 0.05$) values of 0.001 in all the experimental classes, and they reflected the differences in the pretest and posttest digital literacy scores of students after the CoDL-AR instructional design was implemented. These results support that the identified improvements were statistically significant and could be attributed to the use of the instructional model as opposed to the emergence of the same by chance. The collaborative learning and the AR technologies enabled the students to actively participate in digital discovery, communication, and content creation during the science learning activities ([37]; [38]).

Altogether, the results reveal that CoDL-AR instructional design is valid, practical, and effective to enhance digital literacy among primary school students. The instructional design provides online learning experiences that are valuable in terms of collaborative interaction as well as AR visualization. Therefore, these results support the claim that new teaching models that integrate pedagogical collaboration and technology can strengthen 21st-century skills in elementary science education ([39]; [40]; [41]).

4. Conclusion

The findings of this study indicate that the Collaborative Digital Learning–Augmented Reality (CoDL-AR) instructional model is a valid, practical, and promising approach to enhancing digital literacy among primary school students in science education. The content and construct validation results demonstrated that the instructional design was theoretically coherent and supported by expert evaluations, particularly in its integration of collaborative learning principles, augmented reality (AR) technology, and digital literacy competencies. Furthermore, the implementation results confirmed the model's practicality across both limited and extensive trials, as evidenced by high implementation scores and satisfactory reliability. These findings suggest that the instructional stages are sufficiently structured to facilitate classroom implementation and support the integration of collaborative digital activities into primary science learning.

Beyond its validity and practicality, the CoDL-AR model demonstrated promising effectiveness in improving students' digital literacy. The N-Gain analysis revealed moderate-to-high levels of improvement, while the paired-samples *t*-test identified statistically significant differences between

pretest and post-test scores ($p < 0.05$). Taken together, these results provide empirical support for the potential of the CoDL-AR instructional model to strengthen students' digital literacy through the integration of collaborative learning and AR-supported science activities. Rather than positioning AR merely as a visualization tool, the model incorporates digital technologies into collaborative learning processes that encourage students to access and evaluate information, communicate and collaborate digitally, create digital content, and engage with ethical and safety considerations. Accordingly, CoDL-AR offers a promising pedagogical framework for advancing technology-enhanced science education and supporting the development of digital competencies associated with 21st-century learning.

Despite these encouraging findings, several limitations should be acknowledged. First, the study was conducted exclusively in primary school science education, which may constrain the generalizability of the findings to other educational levels, subject areas, and instructional contexts. Second, the implementation of the CoDL-AR model depended on the availability of adequate digital infrastructure and AR-compatible devices. Differences in technological resources, internet connectivity, and institutional readiness may influence the feasibility and effectiveness of the model across schools. Third, the study primarily examined short-term changes in students' digital literacy and did not investigate whether the observed improvements were sustained over time. Consequently, the long-term educational benefits of the CoDL-AR model remain to be established.

In light of these limitations, future research should investigate the long-term effects of the CoDL-AR model on students' digital literacy, including the retention and transfer of digital competencies to other learning contexts. Further studies should also examine the applicability of the model across different educational levels, subject disciplines, and school environments to determine its broader pedagogical value. In addition, researchers could explore the integration of emerging educational technologies and alternative implementation strategies to improve the model's adaptability in schools with varying levels of technological infrastructure. Investigating teacher professional development, implementation fidelity, and contextual factors influencing student outcomes would also provide valuable insights into the conditions required for successful adoption. Overall, the CoDL-AR instructional model represents a promising contribution to digital science education by integrating collaborative pedagogy and augmented reality within a structured instructional framework. Further empirical investigation will be essential to establish its long-term effectiveness, broader applicability, and potential to support sustainable digital literacy development in primary education.

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