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AR-Based SISKOMA Interactive Multimedia for Improving Conceptual Understanding in Junior High School Science

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Abstrak

Penelitian ini bertujuan untuk mengembangkan dan mengevaluasi SISKOMA, multimedia interaktif berbasis Augmented Reality (AR) yang dirancang untuk meningkatkan pemahaman konseptual siswa pada materi Sistem Koordinasi Manusia dalam pembelajaran IPA SMP. Penelitian ini menggunakan metode Research and Development (R&D) dengan model desain pembelajaran ADDIE yang meliputi tahap Analysis, Design, Development, Implementation, dan Evaluation. Penelitian melibatkan 29 siswa kelas IX SMPN 32 Padang yang dipilih melalui purposive sampling. SISKOMA dikembangkan dengan mengintegrasikan teks, audio narasi, animasi, video pembelajaran, kuis interaktif, dan visualisasi tiga dimensi berbasis WebAR dalam satu lingkungan pembelajaran terpadu. Desain multimedia didasarkan pada Cognitive Theory of Multimedia Learning dari Mayer dan Cognitive Load Theory dari Sweller. Instrumen pengumpulan data meliputi lembar validasi ahli, angket praktikalitas guru dan siswa, wawancara, serta tes pretest-posttest. Hasil penelitian menunjukkan bahwa SISKOMA memperoleh kategori sangat valid dari ahli media (87,88%) dan ahli materi (87,5%). Uji praktikalitas menunjukkan respons yang sangat positif dari guru (90,2%) dan siswa. Analisis efektivitas menggunakan rumus normalized gain (N-Gain) memperoleh skor 0,54 dengan kategori sedang. Temuan ini menunjukkan bahwa SISKOMA merupakan multimedia berbasis AR yang layak secara pedagogis dan praktis dalam mendukung pemahaman konseptual siswa terhadap konsep biologi yang abstrak. Penelitian ini juga menegaskan pentingnya integrasi pedagogis, pengelolaan beban kognitif, dan aksesibilitas teknologi dalam mengoptimalkan pembelajaran IPA berbantuan AR.

Kata Kunci: *Augmented Reality; Multimedia Interaktif; Pemahaman Konseptual; Pembelajaran IPA; Sistem Koordinasi Manusia.*

Abstract

This study aimed to develop and evaluate SISKOMA, an Augmented Reality (AR)-based interactive multimedia platform designed to improve students' conceptual understanding of the Human Coordination System in junior high school science learning. The study employed a Research and Development (R&D) approach using the ADDIE instructional design model, consisting of Analysis, Design, Development, Implementation, and Evaluation stages. The research involved 29 Grade IX students at SMPN 32 Padang selected through purposive sampling. SISKOMA was developed by integrating text, narration audio, animations, instructional videos, interactive quizzes, and WebAR-based three-dimensional visualizations within a single instructional environment. The multimedia design was grounded in Mayer's Cognitive Theory of Multimedia Learning and Sweller's Cognitive Load Theory. Data collection instruments included expert validation sheets, teacher and student practicality questionnaires, interviews, and pretest-posttest assessments. The results indicated that SISKOMA achieved a very valid classification from media experts (87.88%) and material experts (87.5%). Practicality assessments showed highly positive responses from teachers (90.2%) and students. Effectiveness analysis using the normalized gain (N-Gain) formula produced a score of 0.54, categorized as moderate improvement. These findings indicate that SISKOMA is a pedagogically feasible and practically accessible AR-based multimedia platform capable of supporting students' conceptual understanding of abstract biological concepts. The study further highlights the importance of pedagogical integration, cognitive load management, and technological accessibility in optimizing AR-supported science learning.

Keywords: *Augmented Reality; Interactive Multimedia; Conceptual Understanding; Science Learning; Human Coordination System.*

INTRODUCTION

The transformative convergence of digital innovation and educational practice has fundamentally restructured instructional paradigms across global learning systems (Selwyn, 2021). Within the conceptual frameworks of Industry 4.0 and Society 5.0, educators are increasingly challenged to move beyond conventional content-delivery methods toward technology-enhanced learning environments that cultivate critical inquiry, digital literacy, collaborative problem-solving, and meaningful conceptual engagement. Indonesia's Merdeka Curriculum reflects this imperative explicitly by positioning technology-integrated learning as a central component of national educational reform.

Despite these structural reforms, science education at the junior high school level continues to encounter a persistent pedagogical challenge related to the abstract nature of biological concepts (Treagust & Duit, 2008). Topics such as the Human Coordination System require students to construct mental representations of anatomical structures and physiological mechanisms that cannot be directly observed through everyday experience. The topic is particularly complex because it involves interconnected processes among the nervous system, sensory organs, endocrine glands, and motor responses that operate simultaneously and dynamically. Understanding these relationships demands not only factual recall but also the ability to visualize spatial structures and causal interactions within the human body. However, conventional instructional media such as textbooks, static diagrams, and presentation slides frequently fail to provide the dynamic and multi-perspective representations necessary for supporting deeper conceptual understanding. As a result, students often develop fragmented conceptual schemas and persistent misconceptions that ultimately affect learning outcomes.

A preliminary investigation conducted at SMPN 32 Padang through classroom observations and teacher interviews confirmed these conditions. Instruction on the Human Coordination System was predominantly delivered through static PowerPoint presentations and pre-recorded videos. Although these media supported basic information delivery, they remained largely passive and provided limited opportunities for interactive conceptual exploration. Students experienced difficulties in visualizing organ structures, understanding physiological processes, and connecting abstract concepts with real biological functions. Student achievement data further indicated that a considerable proportion of learners failed to attain the established Minimum Learning Achievement Criteria (KKTP), suggesting that the difficulties reflected broader conceptual understanding problems rather than isolated individual learning barriers.

Recent developments in educational technology have positioned Augmented Reality (AR) as a promising approach for addressing the abstract nature of science learning. AR enables the real-time integration of digital objects, including three-dimensional models, animations, and interactive overlays, into the physical environment perceived by learners (Azuma, 1997). Through spatial interaction and object manipulation, AR can support experiential and constructivist learning processes that facilitate conceptual visualization (Wu et al., 2013). Previous studies consistently report positive impacts of AR on conceptual understanding, learning engagement, and motivation (Garzón et al., 2019; Radianti et al., 2020). Similar findings have also been reported in Indonesian science education contexts, where AR-based learning media improved student interest and learning outcomes (Fakhrudin & Kuswidyanarko, 2020; Fujiyati et al., 2024; Yusa et al., 2023).

Nevertheless, existing AR-based learning media still reveal several important limitations. Most AR applications primarily function as visualization tools that display three-dimensional objects without integrating them into pedagogically structured learning sequences capable of guiding students toward progressive conceptual understanding. Consequently, AR is often treated as an isolated technological feature rather than as part of a coherent instructional design grounded in learning theory. In addition, many AR platforms require standalone applications, high-specification devices, and stable internet connectivity, conditions that are difficult to fulfill in many resource-constrained school environments (Bacca et al., 2014). Learning activities are also frequently fragmented across multiple platforms, separating content delivery, AR visualization, and assessment into disconnected systems. This fragmentation increases extraneous cognitive load and potentially disrupts the continuity of students' learning experiences (Sweller, 2011). Therefore, the critical issue is no longer simply whether AR can improve learning, but how AR can be pedagogically integrated into accessible and cognitively manageable learning environments that effectively support conceptual understanding in diverse educational contexts.

The theoretical foundations of this study are informed by Mayer's Cognitive Theory of Multimedia Learning (2021) and Sweller's Cognitive Load Theory (2011). Mayer emphasizes that meaningful learning occurs when verbal and visual information are processed through coordinated dual-channel cognitive systems and integrated with learners' prior knowledge. Meanwhile, Cognitive Load Theory explains that instructional materials should minimize unnecessary cognitive demands while optimizing learners' limited working memory capacity for schema construction. These complementary perspectives provide an important foundation for designing multimedia learning environments that not only attract learners' attention but also facilitate effective conceptual processing (Paas & van Merriënboer, 2020).

Based on these considerations, this study developed SISKOMA *(Sistem Koordinasi Manusia)*, an AR-based interactive multimedia platform specifically designed to support conceptual understanding of the Human Coordination System in junior high school science learning. SISKOMA integrates textual explanations, narration audio, animations, instructional videos, interactive quizzes, and WebAR-based three-dimensional visualizations within a single instructional environment developed using Microsoft PowerPoint, WebAR, and Assemblr platforms. Unlike many existing AR applications, SISKOMA was intentionally designed to remain accessible through smartphones and Chromebooks commonly available in Indonesian schools without requiring complex standalone application installation. More importantly, the platform emphasizes the pedagogical integration of AR visualization within a structured multimedia learning sequence that systematically guides students' conceptual construction while managing cognitive load.

Accordingly, this study seeks to examine how accessible WebAR-based interactive multimedia can be pedagogically integrated to support students' conceptual understanding of abstract biological systems. Specifically, the study focuses on the development, validation, practicality, and effectiveness of SISKOMA as a cognitively grounded multimedia learning platform for junior high school science. By integrating accessible AR technology with structured multimedia learning principles, this study contributes not only to the growing discourse on AR-enhanced science learning but also to the development of equitable, pedagogically meaningful, and cognitively supportive digital learning environments for secondary education contexts with limited technological infrastructure.

METHOD

This study employed a Research and Development (R&D) methodology following the ADDIE instructional design model, which encompasses five systematic and iterative stages: Analysis, Design, Development, Implementation, and Evaluation (Branch, 2009). The ADDIE framework was selected because of its structured and evidence-informed approach to instructional product development, its flexibility in accommodating iterative refinement based on expert feedback, and its extensive applicability within educational technology research contexts (Sugiyono, 2019). The research was conducted at SMPN 32 Padang and involved 29 Grade IX students from class IX.E selected through purposive sampling. Participants were intentionally chosen because they had previously studied the Human Coordination System and demonstrated recurring conceptual difficulties identified through teacher evaluation records, preliminary classroom observations, and consultations with the science teacher. Prior to data collection, permission was obtained from the school administration and participating teacher, and all participant data were treated confidentially for research purposes.

During the Analysis stage, a systematic examination of the instructional context was conducted, including an evaluation of existing learning media, analysis of curriculum requirements under the Merdeka Curriculum framework, assessment of learner characteristics and prior knowledge, and identification of conceptual difficulties associated with the Human Coordination System. The findings revealed that instructional practices predominantly relied on static presentation slides and pre-recorded videos, which were insufficient to support the spatial and dynamic visualization demands required for understanding the target concepts.

The Design stage involved the formulation of measurable learning objectives, development of a comprehensive multimedia storyboard, organization of navigation pathways to facilitate self-directed learning, and planning of AR integration points aligned with conceptual learning goals. The multimedia architecture was designed based on Mayer's Cognitive Theory of Multimedia Learning (2021), which emphasizes the integration of verbal and visual information processing, and Sweller's Cognitive Load Theory (2011), which highlights the importance of minimizing extraneous cognitive demands through effective instructional organization, content segmentation, and simplified interface design.

The Development stage was carried out using Microsoft PowerPoint as the primary authoring platform integrated with WebAR technology for browser-based augmented reality delivery and Assemblr for the creation and management of three-dimensional anatomical models. The resulting multimedia product incorporated six instructional components consisting of expository text, contextual images, procedural animations, narration audio, instructional videos, interactive quizzes, and AR-based three-dimensional visualizations of neurological structures such as neurons, the brain, sensory organs, and neural pathways. Following the initial development process, the prototype underwent expert validation involving two media experts and two subject matter experts. The validation process evaluated instructional quality, content accuracy, technical feasibility, visual communication, and alignment with curriculum objectives. Revisions to the multimedia product were subsequently conducted based on validator feedback and recommendations to improve both pedagogical and technical aspects of the system.

The Implementation stage was conducted during regular science instructional sessions in class IX.E at SMPN 32 Padang. All 29 students engaged with SISKOMA using school-provided smartphones and Chromebooks to access the multimedia platform and its WebAR features during classroom learning activities. Simultaneously, practicality assessments were administered to both the classroom science teacher and student participants to evaluate usability, accessibility, interactivity, ease of navigation, and perceived learning support provided by the multimedia system.

The Evaluation stage involved formative and summative evaluation procedures conducted throughout the development and implementation processes. Formative evaluation was carried out continuously through expert validation, teacher feedback, and student practicality assessments to identify areas requiring revision and refinement. Summative evaluation focused on examining the effectiveness of SISKOMA in improving students' conceptual understanding of the Human Coordination System through pretest and posttest assessments.

Data collection procedures employed four primary instruments: expert validation rubrics assessing media and material quality, teacher and student practicality questionnaires, semi-structured interviews with the classroom teacher, and pretest-posttest assessments measuring students' conceptual understanding. Validity and practicality data were analyzed descriptively using percentage calculations and interpreted according to predetermined categorical criteria ranging from low to very high levels of validity and practicality. The effectiveness of the multimedia was determined using normalized gain (N-Gain) analysis, as presented in Equation 1.

$$N - Gain = \frac{\text{Posttest Score} - \text{Pretest Score}}{\text{Maximum Score} - \text{Pretest Score}}$$

Equation 1. Normalized Gain Formula

N-Gain scores were interpreted according to established effectiveness criteria, where scores above 0.70 indicate high effectiveness, scores between 0.30 and 0.70 indicate moderate effectiveness, and scores below 0.30 indicate low effectiveness.

The overall development framework of the SISKOMA interactive multimedia system is illustrated in Figure 1, while the main interface and WebAR-based multimedia display are presented in Figure 2.

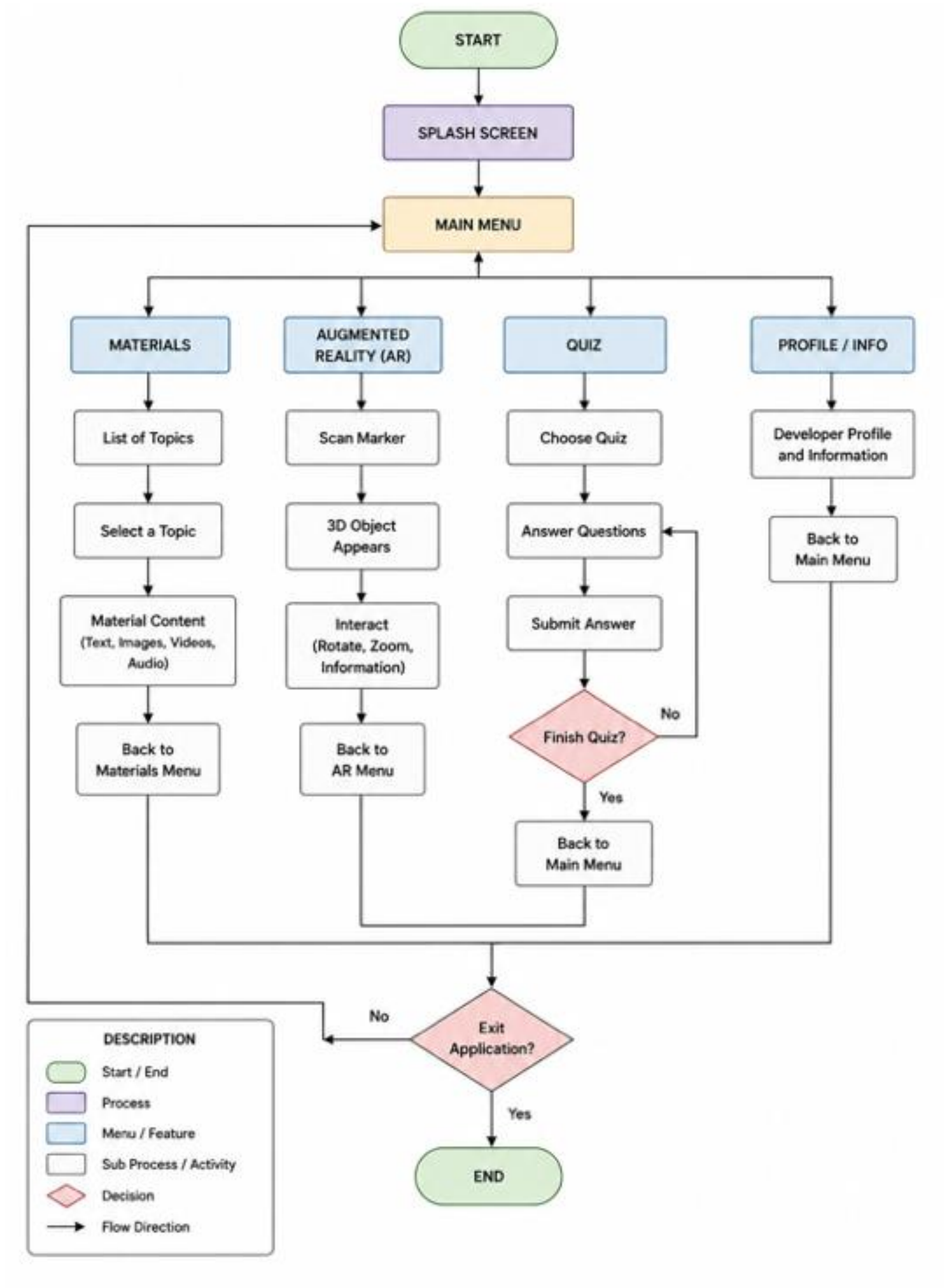

Figure 1. Flowchart of the SISKOMA *Augmented Reality*-Based Interactive Learning Multimedia System

Figure 2. Main Display of the SISKOMA Augmented Reality-Based Interactive Learning Multimedia

RESULTS

The implementation of SISKOMA was integrated into Grade IX science learning sessions at SMPN 32 Padang, focusing on the Human Coordination System topic. Students accessed the multimedia platform using school-provided smartphones and Chromebooks and utilized the WebAR interface to explore three-dimensional models of neurons, brain structures, nervous system architecture, sensory organs, and neural pathways. Classroom observations indicated consistently high levels of student participation and exploratory engagement throughout the instructional sessions. Students actively manipulated AR objects through rotation, zooming, and multi-angle visualization features while collaboratively discussing relationships among organ structures, neural functions, and physiological mechanisms. The multimedia environment also encouraged peer interaction and conceptual discussion during learning activities. Meanwhile, the classroom teacher assumed a facilitative role by providing conceptual guidance and clarification as students navigated the multimedia content. These findings suggest that the integration of interactive multimedia elements and WebAR visualization supported a more active and conceptually oriented learning environment compared with conventional instructional practices.

Student interaction with the SISKOMA multimedia platform during classroom implementation is illustrated in Figure 3.

Figure 3. Students Using SISKOMA Interactive Multimedia During Science Learning

Media Expert Validation

Media expert validation results demonstrated that the developed multimedia achieved a very valid classification, with an average percentage score of 87.88% obtained from two media experts, as presented in Table 1.

Table 1. Media Expert Validation Results

Aspect	Percentage	Category
Visual Design	89.58%	Very Valid
Navigation and Interactivity	93.75%	Very Valid
Audio and Video Quality	87.50%	Very Valid
Animation and AR Features	91.07%	Very Valid
Interactive Quiz	90.63%	Very Valid
Accessibility	87.50%	Very Valid
Average	**87.88%**	**Very Valid**

The highest score was obtained in the navigation and interactivity aspect (93.75%), indicating that the multimedia interface was considered intuitive, interactive, and easy to operate during learning activities. High ratings in animation and AR features further suggest that the WebAR integration successfully supported the visualization of abstract biological concepts through interactive three-dimensional representations. Overall, these findings indicate that the multimedia design fulfilled important instructional and technical quality standards required for science learning media.

Material Expert Validation

Material expert validation produced an average percentage score of 87.5%, categorized as very valid, as shown in Table 2.

Table 2. Material Expert Validation Results

Aspect	Percentage	Category
Curriculum Suitability	90%	Very Valid
Content Accuracy	85%	Very Valid
Material Presentation	93.75%	Very Valid
Evaluation Component	81.25%	Very Valid
Average	**87.5%**	**Very Valid**

The highest rating was observed in the material presentation aspect (93.75%), indicating that the content organization, conceptual sequencing, and multimedia presentation effectively supported instructional delivery. Furthermore, the high curriculum suitability score confirmed that the multimedia content aligned appropriately with the learning objectives and competencies specified within the Merdeka Curriculum framework. These findings suggest that the integration of textual explanations, visual representations, animations, and AR visualization created a pedagogically coherent multimedia environment capable of supporting students' conceptual understanding.

Following the expert validation process and subsequent revisions, the multimedia product was further evaluated through practicality testing involving both teachers and students during classroom implementation.

Practicality Test Results

Teacher practicality assessment results are presented in Table 3, while student response results are shown in Table 4.

Table 3. Teacher Practicality Results

Aspect	Percentage
Ease of Use	90%
Learning Implementation	85%
Curriculum Suitability	93.75%
Technical Accessibility	81.25%
Learning Support	100%
Average	**90.2%**

The teacher practicality results indicate that SISKOMA was highly practical for classroom implementation. The highest score was obtained in the learning support aspect (100%), suggesting that the multimedia effectively assisted instructional delivery and facilitated explanation of abstract biological concepts. Meanwhile, the technical accessibility score, although slightly lower than other aspects, still demonstrated that the multimedia remained accessible and operable within the existing school technological infrastructure.

Table 4. Student Response Results

Aspect	Percentage
Ease of Use	100%
Media Attractiveness	100%
Material Understanding	100%
Interactivity	100%
Learning Motivation	100%
Average	**100%**

Student responses demonstrated extremely positive perceptions toward the SISKOMA multimedia platform across all assessed aspects. The consistently high scores indicate that students perceived the multimedia as highly engaging, interactive, and supportive of conceptual understanding. The strong positive responses may also reflect students' enthusiasm toward the integration of accessible AR-based learning experiences, particularly because the multimedia provided opportunities for direct exploration and visualization of anatomical structures that are typically difficult to observe through conventional instructional media. These findings further suggest that the integration of narration, animation, quizzes, and WebAR visualization within a single learning environment contributed to reducing fragmented learning experiences and supported more focused cognitive engagement during instruction.

Effectiveness Test Results

The effectiveness of SISKOMA multimedia was evaluated through pretest and posttest assessments analyzed using the normalized gain (N-Gain) formula. The results are presented in Table 5.

Table 5. N-Gain Effectiveness Results

Indicator	Score
Average Pretest Score	61.88
Average Posttest Score	82.00
Average N-Gain	0.54
Category	Moderate

Based on Table 5, the obtained N-Gain score of 0.54 falls within the moderate effectiveness category. The increase from an average pretest score of 61.88 to a posttest score of 82.00 demonstrates a meaningful improvement in students' conceptual understanding following the implementation of SISKOMA multimedia. Although categorized as moderate, the results indicate that the integration of structured multimedia elements and WebAR visualization contributed positively to students' ability to understand abstract concepts related to the Human Coordination System. From a cognitive perspective, the findings also suggest that presenting textual explanations, narration, interactive exploration, and three-dimensional visualization within a unified multimedia environment may have supported conceptual processing while minimizing unnecessary cognitive load during learning activities.

DISCUSSION

The empirical findings of this study collectively indicate that SISKOMA constitutes a valid, practically feasible, and moderately effective instructional medium for supporting conceptual understanding of the Human Coordination System in junior high school science learning. The integration of WebAR-based immersive visualization within a structured multimedia learning sequence contributed to measurable improvements in student learning outcomes and received highly positive evaluations from both educational experts and classroom users. Nevertheless, a comprehensive interpretation of these findings requires critical consideration of the pedagogical, cognitive, and contextual factors that shape the effectiveness of AR-assisted learning environments beyond the assumption that technological immersion alone automatically improves learning quality (Akçayır & Akçayır, 2017).

The high expert validation scores, namely 87.88% for media quality and 87.5% for material quality, provide evidence that SISKOMA successfully fulfilled its intended technical, instructional, and curricular design requirements. These findings suggest that the multimedia platform achieved coherent integration among visual design, navigational structure, content presentation, and curriculum alignment within a unified learning environment. However, these validation outcomes should not be interpreted as indicating that the mere presence of AR technology is inherently sufficient to enhance instructional quality. As emphasized by Akçayır & Akçayır (2017), the educational effectiveness of AR depends substantially on how the technology is pedagogically integrated into instructional activities rather than on technological deployment alone. In this study, SISKOMA addressed this concern by embedding AR visualization within a scaffolded multimedia sequence incorporating narration, progressive content segmentation, interactive quizzes, and structured navigation pathways designed to support conceptual learning processes.

The effectiveness analysis produced an N-Gain score of 0.54, categorized as moderate effectiveness. Although this result demonstrates meaningful improvement in students' conceptual understanding, it remains below the high-effectiveness levels reported in several previous AR studies. This outcome likely reflects the interaction of multiple contextual and instructional factors within the present implementation. First, students had limited prior experience using AR technology within formal classroom instruction; consequently, part of their cognitive resources may have been allocated toward technological familiarization rather than conceptual processing. Second, the implementation period was relatively limited, reducing opportunities for repeated exploration, conceptual reinforcement, and gradual schema construction. Third, the Human Coordination System itself represents highly interconnected and abstract biological content that generally requires repeated exposure and multiple representational experiences to support deeper conceptual understanding (Treagust & Duit, 2008). Nevertheless, achieving moderate conceptual improvement within a relatively short intervention period and within conceptually complex learning material remains pedagogically meaningful.

A particularly important issue emerging from this study concerns the management of cognitive load within AR-supported multimedia learning environments. According to Cognitive Load Theory (Sweller, 2011), learners' working memory capacity is inherently limited, and instructional materials generating excessive extraneous cognitive demands may reduce learning efficiency. Classroom observations in the present study suggested that several students tended to allocate considerable attention toward manipulating AR objects through rotating, zooming, and repositioning three-dimensional models, sometimes exceeding their attention toward the conceptual information represented within the visualization itself. This tendency aligns with the seductive detail effect described by Mayer (2021), in which visually attractive multimedia elements may capture learners' attention while unintentionally reducing deeper conceptual processing.

Furthermore, the simultaneous integration of animations, narration, AR visualization, quizzes, and instructional videos introduced the possibility of cognitive overload, particularly for students with limited prior knowledge. This finding contributes an important perspective to AR-based educational research, which has frequently emphasized motivational and engagement benefits while providing comparatively limited attention to the cognitive demands associated with immersive multimedia learning environments. In response to this challenge, SISKOMA incorporated content segmentation strategies, simplified interface structures, and organized navigation pathways intended to reduce unnecessary cognitive burden (Mayer, 2021). However, the moderate effectiveness outcome indicates that optimizing cognitive load management within AR-based multimedia environments remains an important area requiring further refinement.

Technical infrastructure also emerged as a significant contextual factor influencing implementation quality. Although SISKOMA was intentionally designed using WebAR technology to improve accessibility and eliminate the need for standalone application installation, several students experienced unstable internet connectivity, inconsistent AR loading performance, and varying levels of device responsiveness during classroom activities. These technical interruptions occasionally disrupted the continuity of interactive exploration and introduced additional cognitive distractions into the learning process. Such findings reinforce the argument that successful AR integration in classroom instruction depends not only on instructional design quality but also on the technological readiness of the educational environment in which the multimedia is implemented (Bacca et al., 2014).

Another important finding concerns the continuing significance of the teacher's pedagogical role during AR-assisted learning activities. While the multimedia environment encouraged student-centered exploration and active engagement, some learners still required substantial teacher guidance to correctly interpret AR visualizations and connect them meaningfully with underlying scientific concepts. Without adequate instructional scaffolding, the novelty and visual richness of AR environments may potentially function as sources of distraction rather than as supports for conceptual construction. This finding is consistent with Hwang & Chien (2022), who emphasize that technology-enhanced learning environments should complement rather than replace effective instructional facilitation.

In comparative perspective, this study contributes to the growing body of AR-based educational research by positioning AR implementation within a broader pedagogical and cognitive framework emphasizing the balance among immersion, accessibility, and cognitive processing demands. Whereas many previous studies have primarily highlighted motivational benefits and learner engagement, the present study foregrounds the instructional architecture and contextual conditions determining whether immersive AR experiences genuinely support conceptual understanding. In particular, the accessibility-oriented design of SISKOMA demonstrates that pedagogically meaningful AR-based multimedia can be developed using widely available and relatively low-cost technologies suitable for educational environments with limited technological infrastructure (Wu et al., 2013).

Several limitations should nevertheless be acknowledged. The study involved only a single classroom consisting of 29 students, thereby limiting the broader generalizability of the findings. In addition, the relatively short implementation duration did not permit examination of long-term conceptual retention or sustained motivational effects. Furthermore, the present investigation primarily focused on cognitive learning outcomes, while affective, collaborative, and metacognitive dimensions of students' learning experiences remain comparatively underexplored.

Future studies should therefore investigate adaptive AR-based instructional systems capable of dynamically adjusting multimedia complexity according to learners' prior knowledge and cognitive readiness. Longer-term implementations involving larger and more diverse participant populations may also provide deeper insight into the sustained pedagogical impact of AR-assisted multimedia learning across varied educational contexts. In addition, further investigation is needed regarding the pedagogical conditions that most effectively transform immersive AR engagement into durable conceptual understanding, particularly concerning scaffolding strategies, teacher professional development, and assessment integration approaches (Ibáñez & Delgado-Kloos, 2018).

Overall, the findings of this study suggest that the educational value of AR-based multimedia does not primarily reside in immersive visualization alone, but rather in the extent to which such technologies are pedagogically structured to support conceptual processing, cognitive manageability, and contextual accessibility. SISKOMA demonstrates that accessible WebAR integration, when combined with coherent multimedia sequencing and appropriate instructional scaffolding, can contribute meaningfully to conceptual understanding in science learning, particularly within educational contexts characterized by limited technological infrastructure.

CONCLUSION

This study successfully developed and evaluated SISKOMA, an AR-based interactive multimedia platform designed to support conceptual understanding of the Human Coordination System in Grade IX junior high school science learning. Developed using the ADDIE framework and grounded in Mayer's Cognitive Theory of Multimedia Learning and Sweller's Cognitive Load Theory, SISKOMA integrates text, narration audio, animations, instructional videos, interactive quizzes, and WebAR-based three-dimensional visualization within an accessible instructional environment.

The findings showed that SISKOMA achieved high levels of validity and practicality, indicating that the multimedia was technically feasible, instructionally coherent, and aligned with curriculum objectives. The effectiveness evaluation produced a moderate improvement in students' conceptual understanding, suggesting that the integration of structured multimedia elements and accessible WebAR visualization contributed positively to learning abstract biological concepts.

This study also highlights that the effectiveness of AR-based multimedia is influenced not only by immersive visualization, but also by cognitive load management, technological accessibility, and teacher facilitation during learning activities. Therefore, the educational value of AR lies in how the technology is pedagogically integrated to support meaningful conceptual understanding within cognitively manageable learning environments.

Overall, SISKOMA represents a pedagogically grounded and practically viable instructional innovation for science education, particularly in educational contexts with limited technological infrastructure. Future research is recommended to involve larger participant populations, extend implementation duration, and examine the long-term impact of AR-based multimedia on conceptual retention and science learning engagement.

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