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Semiotics-based augmented reality learning media for visualizing three-dimensional geometry to support mathematical literacy among deaf learners

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Abstract

Mathematics learning for deaf learners, particularly in three-dimensional geometry, remains challenging because abstract concepts are commonly presented through two-dimensional instructional materials that do not adequately support visual learning. This study aimed to design, develop, and validate a semiotics-based Augmented Reality (AR) learning medium to support deaf learners' understanding of three-dimensional geometry. The study adopted the Lee and Owens instructional design model, comprising the phases of analysis, design, development, implementation, and evaluation. Front-end analysis involved curriculum review, classroom observations, teacher interviews, and needs analysis with 29 deaf learners to establish the design specifications of the learning media. Data were collected using expert validation questionnaires, classroom observation sheets, teacher and student response questionnaires, and comprehension assessment sheets during a pilot implementation involving seven deaf junior high school students. The developed media achieved an overall expert validity score of 91.2% (Very Valid). Teacher and student responses indicated that the media was practical for classroom use. In contrast, students obtained an average comprehension score of 83.33% on the geometry comprehension assessment, indicating that the developed media effectively supported their understanding of three-dimensional geometry. These findings suggest that integrating semiotic principles with Augmented Reality provides meaningful visual representations that facilitate the learning of abstract geometry concepts for deaf learners. This study contributes to the development of inclusive mathematics learning media and provides a foundation for future large-scale implementation and evaluation.

Keywords:
Augmented reality, Deaf student, Mathematical literacy, Semiotics

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1. INTRODUCTION

Deaf learners primarily rely on visual communication and often experience limited access to spoken language during classroom instruction, making visually rich learning environments particularly important for mathematics education (Pabis & Catalano, 2023; Rahmawati & Pamungkas, 2023; Santos & Cordes, 2022). Mathematics instruction for Deaf students should capitalize on their visual strengths rather than relying primarily on verbal explanations. Abstract mathematical concepts can be represented through symbols, diagrams, graphs, and spatial relationships, all of which require meaningful visual interpretation. Effective mathematics instruction therefore integrates visual representations, sign language, gestures, and interactive media to facilitate conceptual understanding. Previous research has shown that visual and multimodal instructional approaches improve Deaf students' access to mathematical concepts by reducing linguistic barriers while strengthening spatial reasoning and mathematical communication (Healy et al., 2016; Krause & Wille, 2021). Consequently, mathematics instruction should not simply translate verbal explanations into sign language; instead, it should be designed using media that integrate signs, indices, and symbols to construct visual meaning and support conceptual development.

Deaf learners construct mathematical understanding through visual representations, which requires learning media that systematically organize signs and meanings. Semiotics provides a theoretical foundation for explaining how learners interpret mathematical ideas through signs, symbols, diagrams, gestures, and other forms of representation. In mathematics education, symbolic notation explains how learners construct meaning from various representations and transform visual information into conceptual understanding (Godino et al., 2022; Purwasih et al., 2023; Purwasih et al., 2024). This perspective is particularly relevant for deaf learners because mathematical communication relies heavily on visual sign systems, rather than spoken language, making visually meaningful learning media crucial for effective mathematics instruction. Among various semiotic theories, Peirce's triadic model offers a particularly appropriate framework, as it explains the construction of meaning through icons, indices, and symbols (Suryaningrum et al., 2023). These three categories provide practical principles for representing abstract mathematical concepts in visual learning environments. Peirce's semiotics serves as the conceptual foundation for the proposed Augmented Reality application. Peirce considered semiotics closely related to logic, emphasizing that human reasoning operates through signs (Poythress, 2022). This perspective suggests that learners construct, communicate, and interpret mathematical meaning through interconnected sign systems, making Peirce's semiotic framework highly appropriate for designing visually accessible mathematics learning media for deaf learners.

Although semiotics explains how mathematical meaning is constructed through signs and representations, learning media are still needed to transform semiotic principles into meaningful learning experiences. Augmented Reality (AR) offers such a medium by integrating virtual three-dimensional objects with real-world environments, allowing learners to interact with mathematical representations in authentic contexts. In mathematics education, AR supports the visualization of abstract concepts, such as three-dimensional geometry, by allowing students to manipulate virtual objects, explore various representations, and connect symbolic mathematical ideas with concrete visual experiences. AR development is particularly

well-suited for deaf learners, whose learning relies heavily on visual and spatial information processing. According to Peirce, individuals think through signs, which enables them to communicate with one another and to ascribe meaning to phenomena in their environment (Li & Yu, 2023; Samaranayake, 2025). From a design perspective, Peirce's triadic model provides a practical framework for translating semiotic theory into Augmented Reality (AR)-based mathematics learning. In the proposed learning medium, icons are represented through three-dimensional virtual models of geometric objects that visually resemble real-world objects, enabling learners to recognize mathematical forms directly. Indexes are operationalized through sign-based interactions and object manipulation, which establish contextual relationships between physical learning materials and virtual mathematical representations. Symbols are represented through mathematical notation, formulas, labels, and textual explanations, supported by sign language, enabling learners to construct abstract mathematical meaning from visual experiences. These three semiotic components are systematically integrated to support learners in progressing from concrete visual perception to abstract mathematical reasoning. Thus, the AR learning environment is not only for displaying three-dimensional objects but also to facilitate the interpretation of meaning through icons, indices, and symbols. This semiotic design framework serves as a conceptual basis for developing AR learning media.

Augmented Reality (AR) offers such a medium by integrating virtual three-dimensional objects with real-world environments, allowing learners to interact with mathematical representations in authentic contexts. In mathematics education, AR supports the visualization of abstract concepts, such as three-dimensional geometry, by allowing students to manipulate virtual objects, explore various representations, and connect symbolic mathematical ideas with concrete visual experiences (Mandala et al., 2025; Nindiasari et al., 2024). AR development is particularly well-suited for deaf learners, whose learning relies heavily on visual and spatial information processing. Therefore, integrating semiotic principles into AR-based mathematics learning can provide visually meaningful learning experiences that support conceptual understanding among deaf learners. Augmented Reality (AR) allows students to visualize and manipulate three-dimensional representations of geometric objects, thereby facilitating the exploration of abstract mathematical concepts through concrete and interactive experiences (Bulut & Borromeo Ferri, 2023; İslim et al., 2024). Previous research has shown that AR enhances mathematics learning by promoting three-dimensional visualization, increasing student engagement, enhancing spatial reasoning, and providing immersive learning experiences, particularly in geometry (Kuncoro et al., 2024; Pahmi et al., 2023). By connecting abstract mathematical representations with interactive visual experiences, AR creates a meaningful learning environment where students can explore, manipulate, and interpret mathematical concepts more effectively.

Numerical literacy refers to an individual's ability to understand, use, and interpret mathematical concepts and operations in a variety of real-life contexts (Ahyan et al., 2025; Asmara et al., 2026; Setiyani et al., 2025). This competency encompasses skills in identifying quantitative information, analyzing data, solving problems, and making critical and logical decisions based on evidence. Numeracy literacy also emphasizes conceptual understanding that enables individuals to connect mathematics to real-world situations (Fauzan et al., 2024;

Hidayah et al., 2025; Yerizon et al., 2025). Thus, numeracy literacy serves as a key competency that supports active participation in modern society and encourages rational decision-making. In this study, mathematical literacy is conceptualized in line with the PISA mathematical literacy framework, which defines it as an individual's ability to formulate, use, and interpret mathematics across a variety of real-world contexts (OECD, 2023). The AR learning media developed has the potential to support mathematical literacy by helping deaf students interpret, visualize, and apply three-dimensional geometric concepts in meaningful learning contexts.

The literacy and numeracy levels of deaf children are significantly lower than those of their hearing peers (Henner et al., 2021; Shusterman et al., 2022). These challenges are largely attributed to limited access to language during early childhood and restricted opportunities for meaningful communication, which may delay language development and subsequently affect mathematical learning and literacy achievement (Henner et al., 2021; Santos & Cordes, 2022; Shusterman et al., 2022). Hearing impairments lead to delays in language acquisition, which, in turn, affect the understanding of abstract and symbolic concepts that underpin literacy and numeracy learning. Moreover, conventional mathematics instruction, which predominantly relies on spoken explanations and auditory interaction, often limits Deaf learners' access to mathematical discourse and classroom participation. Studies have shown that instruction lacking accessible visual and signed communication can hinder conceptual understanding and contribute to persistent disparities in mathematics achievement between Deaf and hearing learners (Hoffmeister et al., 2022; Krause & Wille, 2021). Recent research consistently reports that deaf students face significant barriers to mathematics learning due to limited access to effective communication and the scarcity of visually oriented learning materials. For example, Krause (2023) argues that mathematics education is still dominated by spoken language, which limits deaf students' epistemological access to mathematical discourse and meaningful classroom participation, while Fadhila et al. (2024) identified inadequate visual learning media as a major communication barrier to mathematics learning in inclusive classrooms. Furthermore, recent studies have shown that Augmented Reality (AR), through its interactive visual representations, can enhance the conceptual understanding, learning engagement, and participation of deaf students by providing visually accessible learning experiences that align with their communication and learning characteristics (Andriyani et al., 2022; Bulut & Borromeo Ferri, 2023; İslim et al., 2024). These findings underscore the importance of developing semiotic-based Augmented Reality learning media to support meaningful mathematics learning.

To date, the literacy practices of deaf students in schools have not demonstrated effective use of media as tools for literacy activities or as sources of learning, nor has there been adequate follow-up after literacy-related activities. Numeracy literacy is particularly important for deaf children as it enables them to communicate using mathematical numbers and symbols and to solve problems encountered in daily life (Langdon et al., 2023). Given the challenges deaf students face in developing numeracy skills, innovative learning media that utilize signs and symbols can provide a more accessible pathway for understanding mathematical concepts.

Internationally, Learning challenges among deaf students have consistently been linked to limited access to accessible visual and interactive learning media, which limits opportunities for meaningful language learning and the development of abstract mathematical concepts. Recent studies have shown that learning environments dominated by spoken language and conventional teaching materials often reduce deaf learners' participation in mathematical discourse and conceptual understanding (Hoffmeister et al., 2022; Krause & Wille, 2021). To address these challenges, several researchers have studied the use of visual-oriented technologies, including animation and augmented reality (AR). Research results (Bulut & Borromeo Ferri, 2023; İslim et al., 2024; Kuncoro et al., 2024) indicate that AR can enhance visual representation, spatial reasoning, conceptual understanding, and student engagement, particularly in geometry learning. In addition, research by Andriyani et al. (2022) found that AR-based visual learning environments facilitate conceptual understanding and increase deaf learners' participation in learning. Studies conducted in Indonesian special schools have reported that mathematics learning for Deaf learners continues to face communication barriers, limited access to visual learning resources, and challenges in implementing student-centered instructional approaches (Fadhila et al., 2024; Mahayukti & Dewi, 2022). These findings highlight the need to develop innovative learning media capable of dynamically visualizing mathematical concepts, for example, through animations or videos, thereby serving as a literacy and numeracy tool that enables children with hearing impairments to build more concrete and meaningful conceptual understanding.

Previous research provides a strong theoretical foundation for integrating semiotic-based augmented reality (AR) into learning for children with hearing impairments. Lim and Lim (2020) outlined a semiotic framework for AR that highlights how signs and representations support learners' meaning-making processes, thus establishing a crucial foundation for designing AR-based learning media. Similarly, Wang and Tan (2023) offer a multimodal and semiotic analysis of user interactivity in AR-assisted learning, highly relevant for developing mathematics learning experiences that effectively integrate visual and symbolic representations. Research on semiotics by Suryaningrum et al. (2021) further demonstrates that math games based on semiotic principles can stimulate children's understanding of mathematical concepts.

While the three studies have made important contributions to learning using AR media, these studies are limited to developing explicit mathematics learning media and have not integrated semiotic principles into AR environments specifically designed to support mathematical literacy for deaf learners. This gap provides the rationale for this study. Therefore, this study aims to develop and validate a semiotic-based Augmented Reality learning medium based on semiotic theory and visual learning principles to support mathematical literacy among deaf learners. Specifically, this study aims to (1) develop a semiotic-based Augmented Reality learning medium based on semiotic theory and visual learning principles, (2) evaluate its validity and practicality through expert review and pilot implementation, and (3) test how the developed medium supports mathematical literacy among deaf learners through interactive visual representations.

2. METHOD

2.1. Research Design

The semiotics-based Augmented Reality (AR) learning media were developed in Jember Regency, involving participants from Special Needs Schools (SLB) and Inclusive Schools. This study employed a development research design adapted from the multimedia instructional design model proposed by Lee and Owens (2004). The model was selected because it provides a systematic framework specifically designed for developing multimedia-based instructional products, with a comprehensive front-end analysis that facilitates the identification of learners' characteristics, instructional needs, and media requirements before the design process. These characteristics make the model particularly suitable for developing semiotics-based AR learning media for Deaf learners. The development process consisted of five stages: (1) analysis, (2) design, (3) development, (4) implementation, and (5) evaluation. A detailed description of each stage is presented in Table 1.

Table 1. Implementation of the Lee and Owens model in developing the semiotics-based AR learning media

Stages	Activity
Analysis	Conducting a preliminary analysis involving 29 deaf students from special and inclusive schools to identify learning difficulties in three-dimensional geometry, characteristics of deaf students, technological readiness, curriculum requirements, and the need for visually meaningful learning media. Literature on mathematical literacy, semiotics, and reality was reviewed to build a theoretical foundation for the learning media.
Design	Designing learning flows, user interfaces, learning scenarios, storyboards, and semiotic frameworks for AR applications based on Peirce's triadic model (icons, indices, and symbols). Learning activities are aligned with selected mathematical literacy, specifically conceptual understanding, mathematical representation, and spatial reasoning in three-dimensional geometry.
Development	Developed the Android-based AR application including 3D geometric models, AR interactions, mathematical representations, sign-language-supported explanations, learning worksheets, and teacher guidance. The prototype was then validated by experts in mathematics education, educational technology, and special education before revision.
Implementation	Conducting an implementation trial involving seven deaf junior high school students to evaluate the usability, practicality, and learning interaction of the AR media developed during classroom learning.
Evaluation	Formative evaluations are conducted based on input from experts, classroom observations, and teacher feedback. The evaluation results are used to revise the learning media and improve its content, interaction design, and instructional components before wider implementation.

The Lee and Owens instructional design model was chosen because it was specifically developed for multimedia-based learning design and provides systematic guidance for designing, developing, implementing, and evaluating technology-enhanced learning resources (Lee & Owens, 2004). The Lee and Owens model incorporates a comprehensive initial analysis to identify learner characteristics, learning needs, technology readiness, learning tasks, and environmental conditions before product development begins. This detailed analysis supports the development of learning media aligned with learner needs, learning objectives,

and the characteristics of multimedia-based learning. Therefore, the Lee and Owens model was deemed appropriate for developing the semiotics-based Augmented Reality mathematics learning media used in this study. The overall development process is illustrated in Figure 1.

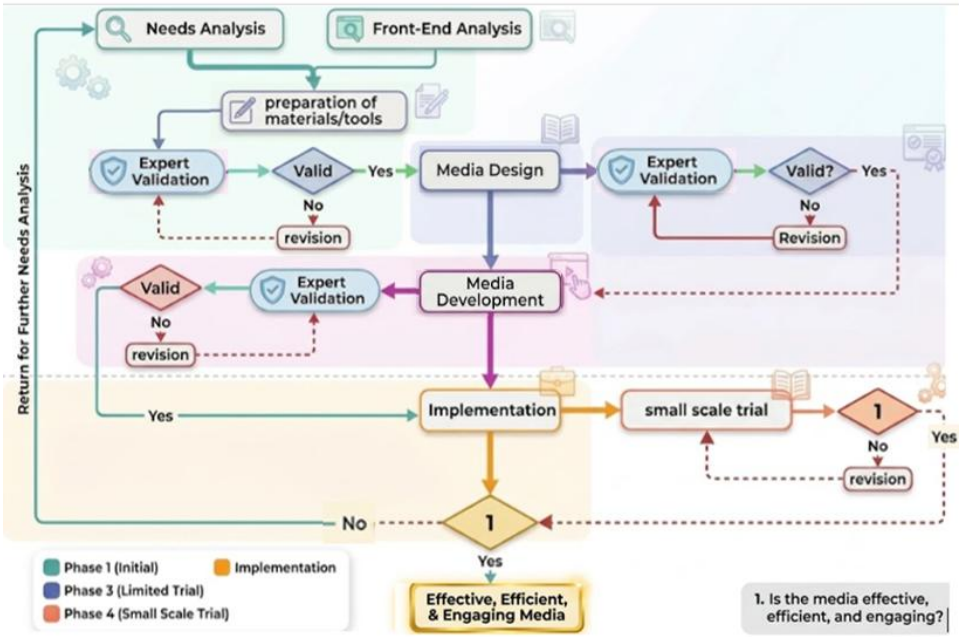


Figure 1. Multimedia development design process

The research procedure was adapted from Lee and Owens' instructional design model. This study was limited to expert validation and small-scale implementation. Large-scale implementation is proposed as a future research direction.

2.2. Research Participant

Participants were purposively selected based on the following inclusion criteria: (1) students with hearing impairments enrolled in special or inclusive schools, (2) able to operate Android devices, and (3) willing to participate in the study. The number and characteristics of participants varied at each development phase to suit the specific objectives of each phase. During the needs analysis, 29 deaf students from elementary schools (n = 8), junior high schools (n = 13), and senior high schools (n = 8) participated to identify learner characteristics, learning needs, and learning preferences at various levels of education a small-scale trial involved seven deaf students from a special junior high school in Jember. In accordance with the objectives of the development research, this phase was intended to evaluate the usability, practicality, and feasibility of the developed AR learning media, not its learning effectiveness. A small sample size (n = 7) was deemed adequate to identify usability issues and obtain formative feedback for product improvement. Participants for the small-scale trial were drawn from a subgroup of junior high schools involved in the needs analysis because they met the inclusion criteria and were available during the implementation phase. A larger-scale implementation involving a broader sample is planned for future studies to evaluate learning effectiveness and provide generalizable statistical evidence.

2.3. Instruments for Data Collection

Three categories of instruments were used to collect data during the development process.

a. Needs Analysis Instrument.
   Data were collected using a structured needs analysis questionnaire and a semi-structured interview guide. The questionnaires were used to explore students' learning difficulties in three-dimensional geometry, prior experience with digital learning media, access to mobile technology, visual learning preferences, and perceived needs related to mathematics learning using semiotics-based AR. Semi-structured interviews with mathematics teachers were conducted to identify teaching challenges, student characteristics, existing teaching practices, and expectations related to the development of semiotics-based Augmented Reality (AR) learning media.

b. Expert Validation Instrument.
   The developed learning media was evaluated using an expert validation form completed by four experts: a mathematics education expert, an educational technology expert, a language expert, and a special education expert experienced in teaching deaf students. Each expert evaluated aspects relevant to their area of expertise using a five-point Likert scale and provided qualitative suggestions for product improvement.

c. Pilot Test Instrument.
   During the trial, data were collected using (a) a structured classroom observation sheet, (b) a student response questionnaire, and (c) a teacher response questionnaire. The observation sheets documented students' interactions with the semiotic-based AR media, participation during learning activities, task completion, and observable learning behaviors. The student and teacher questionnaires evaluated the usability, practicality, accessibility, and benefits of the semiotic-based AR media developed for mathematics learning.

2.4. The Data Analysis

Quantitative and qualitative data collected during the analysis, validation, and trial stages were analyzed according to the objectives of each phase of the development process. Quantitative data obtained from the expert validation form, student response questionnaire, and teacher response questionnaire were analyzed using descriptive statistics by calculating average scores and percentages for each assessment aspect. The resulting scores were then interpreted using predetermined criteria to assess the validity and practicality of the developed learning media. A five-point Likert scale was used as the response measurement scale, while descriptive statistical analysis was used to summarize and interpret the quantitative findings.

Data collected during the trial through classroom observations were analyzed descriptively to examine student interactions with the semiotic-based AR media, class participation, task completion, and observable learning behaviors during mathematics learning. These findings were used as formative evaluation data to support product refinement, not to determine teaching effectiveness. Qualitative comments and suggestions provided by experts, teachers, and students were analyzed thematically and incorporated into subsequent revisions of the learning media. The interpretation criteria used to classify the validity and

practicality of the developed learning media are presented in Table 2. At the same time, the trial findings are reported as formative evidence to support product refinement.

Table 2. Validity classification of the product

Validity Criteria	Validity Level
85.01% - 100%	Very Valid
70.01% - 85%	Valid
50.01% - 70%	Not Valid
1% - 50%	Very Not Valid

The practicality of the product was evaluated based on the outcomes of the teacher questionnaires, using the following classification scheme (see Table 3).

Table 3. Practicality classification of the product

Practicality Criteria	Level of Practicality
81% - 100%	Very Practical
61% - 80%	Practical
41% - 60%	Not Practical
1% - 40%	Very Not Practical

The effectiveness of the instructional material was determined through behavioral observations of children during project-based learning sessions. The level of learning mastery was interpreted according to the following scale (see Table 4).

Table 4. Effectiveness classification of the module

Effectiveness Criteria	Category
81% - 100%	Very Effective
61% - 80%	Effective
41% - 60%	Not Effective
1% - 40%	Very Not Effective

According to these criteria, the developed instructional module is considered effective when students' learning performance achieves a minimum rating within the effective category or higher.

3. RESULTS AND DISCUSSION

3.1. Results

The AR-based semiotic media developed in this study is an application called Three-Dimensional Geometry. This application enables students to visualize three-dimensional geometric shapes through an Android-based mobile device. The development of the semiotics-based Augmented Reality (AR) learning media followed a series of organized steps. These stages include: (1) analysis, (2) design, (3) development, (4) implementation, and (5)

evaluation. The detailed description of each stage in the development of the semiotics-based AR media is presented as follows.

3.1.1. Front-End Analysis

An initial analysis was conducted during the analysis phase of Lee and Owens' instructional design model to identify instructional requirements for developing the proposed semiotics-based Augmented Reality (AR) learning media. Data were collected through a needs analysis questionnaire completed by 29 Deaf students, classroom observations, interviews with mathematics teachers, and analysis of curriculum documents. The analysis focused on six aspects: (1) learner characteristics (audience analysis), (2) learning context (situation analysis), (3) existing instructional technology (technology analysis), (4) curriculum requirements (task analysis), (5) instructional problems (issue analysis), and (6) expected learning outcomes (objective analysis). Findings from each aspect were used to establish the design specifications and instructional requirements for the developed AR learning media. The results of the initial analysis are presented.

a. Audience

Questionnaire responses from 29 deaf students indicated that 24 (82.8%) had difficulty understanding three-dimensional geometry solely through textbook illustrations and teacher explanations. Interviews with mathematics teachers revealed that students often relied on concrete objects and visual demonstrations to understand geometric concepts. These findings suggest that deaf students need learning media that present mathematical concepts through visual and interactive representations rather than solely through verbal explanations. Consistent with the characteristics of visual learning among deaf students, three-dimensional representations can facilitate conceptual understanding by reducing reliance on spoken language.

b. Situation

Interviews with teachers revealed that mathematics instruction was primarily delivered through verbal explanations accompanied by static visual materials. Further classroom observations revealed that students had difficulty interpreting two-dimensional representations of three-dimensional objects. These findings demonstrate a mismatch between the visual learning characteristics of deaf students and the learning media currently used in mathematics classes.

In delivering instructional content to deaf students, it is necessary to develop teaching aids that utilize Augmented Reality (AR) technology as a three-dimensional (3D) animation-based learning medium. The use of 3D media in education is highly beneficial in enhancing both student interest and learning outcomes, particularly for students with hearing impairments.

c. Technology

In mathematics instruction at Special Schools for the Deaf (SLB-B), teachers primarily use PowerPoint presentations or traditional whiteboards. However, deaf students require more appropriate technology to support effective learning in mathematics. Augmented Reality (AR)

with interactive animations can help students deepen their understanding of concepts, increase engagement, and provide a more effective learning solution.

d. Task Analysis

A task analysis was conducted through teacher interviews to identify the mathematics tasks assigned to deaf students during three-dimensional geometry lessons. Classroom observations and teacher interviews revealed that many students struggled to complete the tasks given by teachers because teaching practices relied on textbooks and teacher explanations. Students were able to identify geometric objects but struggled to visualize the three-dimensional structure of two-dimensional images and connect visual representations to mathematical concepts. The results of this task analysis served as the basis for designing semiotics-based mathematics learning media with augmented reality to facilitate students' conceptual understanding of three-dimensional geometry.

e. Issue Analysis

Deaf students face considerable challenges in understanding mathematics when it is presented in abstract form. They require learning materials that are clear, concise, easily comprehensible, and appropriately tailored to their educational stage. For students with additional learning limitations, the content can be further simplified or the level of difficulty reduced in certain sections to align with their abilities.

f. Goal Analysis

The objective analysis was conducted by reviewing the mathematics curriculum for junior high school students to identify learning objectives relevant to three-dimensional geometry. The analysis revealed that achieving the curriculum objectives requires learning experiences that encourage visual exploration, conceptual understanding, and meaningful connections between concrete objects and abstract mathematical representations. Therefore, semiotics-based augmented reality learning media was designed to support these curriculum objectives by providing interactive visual representations that facilitate students' understanding of three-dimensional geometry while strengthening their mathematical literacy.

3.1.2. Design

a. Book Design

The book developed in this study is entitled Three-Dimensional Geometry and is designed as a pocket book containing the basic concepts of three-dimensional geometric shapes. The book also serves as a marker in the 3D application, enabling it to generate 3D objects when integrated. The Three-Dimensional Geometry pocket book is displayed in Figure 2.

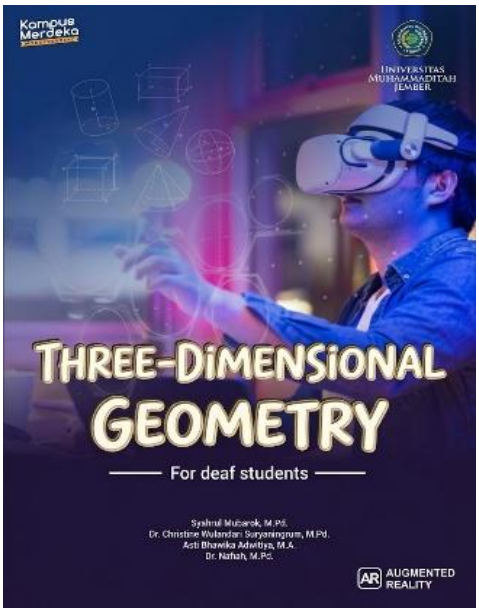


Figure 2. Book design

b. Application Design

To ensure that the developed application provides a coherent and intuitive learning experience, a flowchart was designed before the implementation phase. The flowchart defined the sequence of user interactions, organized navigation between application features, and ensured that each learning activity aligned with the learning objectives derived from the curriculum and the semiotic design framework. Establishing the interaction flow during the design phase also facilitates the integration of Augmented Reality components, learning content, and visual representations into a consistent learning process. The resulting application design flowchart is presented in Figure 3.

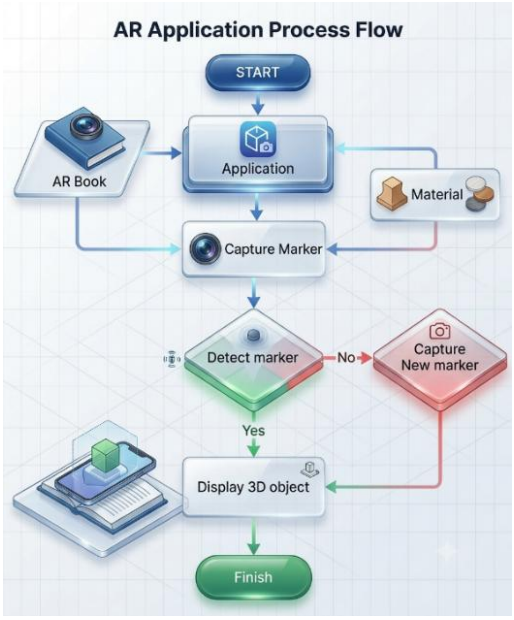


Figure 3. Flowchart of the user interface (UI) of the spatial structure

3.1.3. Development of AR Media Based on Semiotics

The development phase aims to produce semiotics-based Augmented Reality (AR) learning media to support students with hearing impairments in understanding three-dimensional geometry concepts. The media was developed based on product specifications established during the design phase, integrating these principles into visual representations, content structure, and user interaction mechanisms. Each component of the media was developed systematically to deliver concrete, easy-to-interpret concepts aligned with the visual learning characteristics of students with hearing impairments.

a. Development of Pocket Book, Image Assets, and Markers

The instructional content was developed as a pocket guide containing material descriptions, visual illustrations, instructions for using the media, and markers serving as visual triggers in the Augmented Reality application. The material was organized in accordance with the learning outcomes for three-dimensional shapes and presented using simple language with a strong emphasis on visual representations. Each marker was designed to be highly legible so that it could reliably support object identification while the application was operating. In this stage, CorelDRAW was utilized to produce optimal designs. The process involved developing the pocket book, creating graphic assets, and designing markers to enhance the user experience.

b. Development of 3D Objects

Three-dimensional object representations were developed to visualize abstract concepts of three-dimensional shapes in more concrete and interactive visual forms. Each object was designed based on the characteristics of the three-dimensional shapes being studied, taking into account the accuracy of form, proportions, orientation, and visual attributes. The development of these representations integrates semiotic principles through the interconnection between visual signs, mathematical objects, and the user's interpretive process, thereby helping students build a more meaningful conceptual understanding.

c. Development of User Interface (UI) Design

This phase focuses on integrating all media components, including learning content, markers, three-dimensional object representations, and the user interface, into a single Augmented Reality-based learning system (see Figure 4). The user interface (UI) is designed with an emphasis on navigational simplicity, visual consistency, and ease of interaction to accommodate the characteristics of deaf students. Additionally, interaction mechanisms are developed to allow users to access virtual representations in real time by scanning markers, ensuring that the process of exploring concepts is active and contextual.

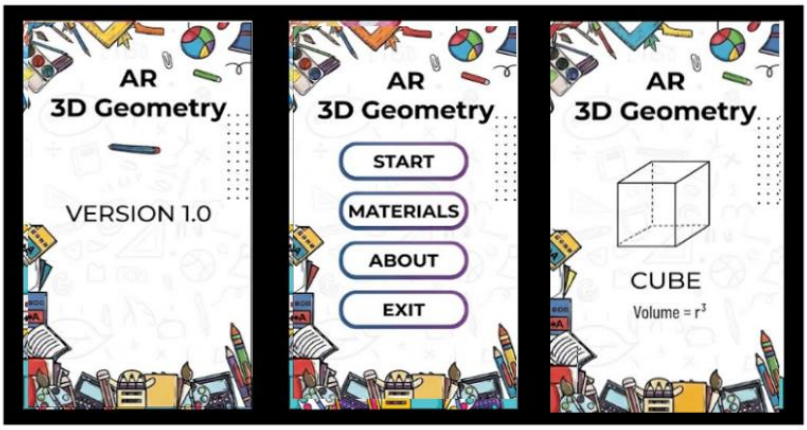


Figure 4. Initial product development result design

d. Expert Validation Results

1) Deaf Expert

The validity score for the semiotic-based AR media was calculated by averaging the scores provided by the Deaf Experts. The overall average validity score was 4.58 out of 5.00 (91.5%), indicating that the developed media meets the Highly Valid category (see Table 5). The validation results from deaf experts indicate that the semiotics-based AR media meets the criteria for excellent performance across all key indicators. The clarity and consistency of symbols, signs, and visual representations were rated highly, as was the appropriateness of the sign language used. Visual legibility was rated good, with minor suggestions for improving color contrast and proportionality. The media exhibited strong alignment between text, images, and symbols. These findings indicate that the semiotics-based Augmented Reality learning media met the required standards in terms of content, media design, language, and accessibility before the pilot implementation. Overall, the media was deemed very suitable for use, requiring only minor visual improvements.

Table 5. Deaf expert validation results

No	Criteria	Score
1	Material Feasibility	4.1
2	Eligible Contents	4.8
3	Supporting Learning Material	4.6
4	Sophistication of Material	4.8
	Average	4.58

2) Content Expert

The content expert's evaluation based on four components yielded an average score of 4.6 (92%), categorized as Very Valid (see Table 6). This result indicates that the learning content aligns with curriculum objectives, learning indicators, and mathematical concepts, while requiring only minor improvements.

Table 6. Content expert validation results

No	Rated aspect	Score
1	Alignment with Learning Objectives	4.7
2	Accuracy of Mathematical Concepts	4.8
3	Content Organization and Coherence	4.6
4	Support for Mathematical Literacy	4.5
5	Appropriateness for Deaf Learners	4.4
	Average	4.6

3) Media Expert

The media expert validation results yielded an average score of 4.50 (90.0%), indicating that the semiotic-based AR media was Highly Valid (see Table 7). The visual design, layout, ease of use, and proportion of visual elements were all rated highly, indicating that the application was visually appealing, well-organized, and easy to use by teachers and students. Accessibility was rated good, with the expert suggesting minor improvements to make the media more adaptable and usable in various inclusive classroom environments.

Table 7. Media expert validation results

No	Rated aspect	Score
1	Visual Design	4.8
2	Layout	4.8
3	Ease of Use	4.6
4	Accessibility	4.1
5	Size and Proportion	4.2
6	Appeal	4.5
	Average	4.5

4) Language Expert

Language experts gave an average score of 4.73 (94.5%), indicating that the language component was highly valid (see Table 8). The evaluation focused on the language's appropriateness to students' cognitive and socio-emotional development. Readability and clarity indicated that instructions and explanations were easy to understand. The results indicate that the language used was easy to understand and supported effective communication for deaf learners.

Table 8. Language expert validation results

No	Rated aspect	Score
1	Language suitability	4.8
2	Communicative	4.8
3	Coherence	4.6
4	Integrity	4.7
	Average	4.73

Overall, the four expert evaluations yielded an average validity score of 4.6 (92%), categorized as Very Valid. The consistently high scores across the four experts indicate that the developed learning media meets the requirements of content quality, media design, language, accessibility, and usability. Therefore, the semiotic-based AR media is considered suitable for implementation after making minor revisions suggested by the experts.

Based on expert validation results, the researchers revised the AR media. The following presents the revisions made in response to the experts' feedback (see Figure 5).

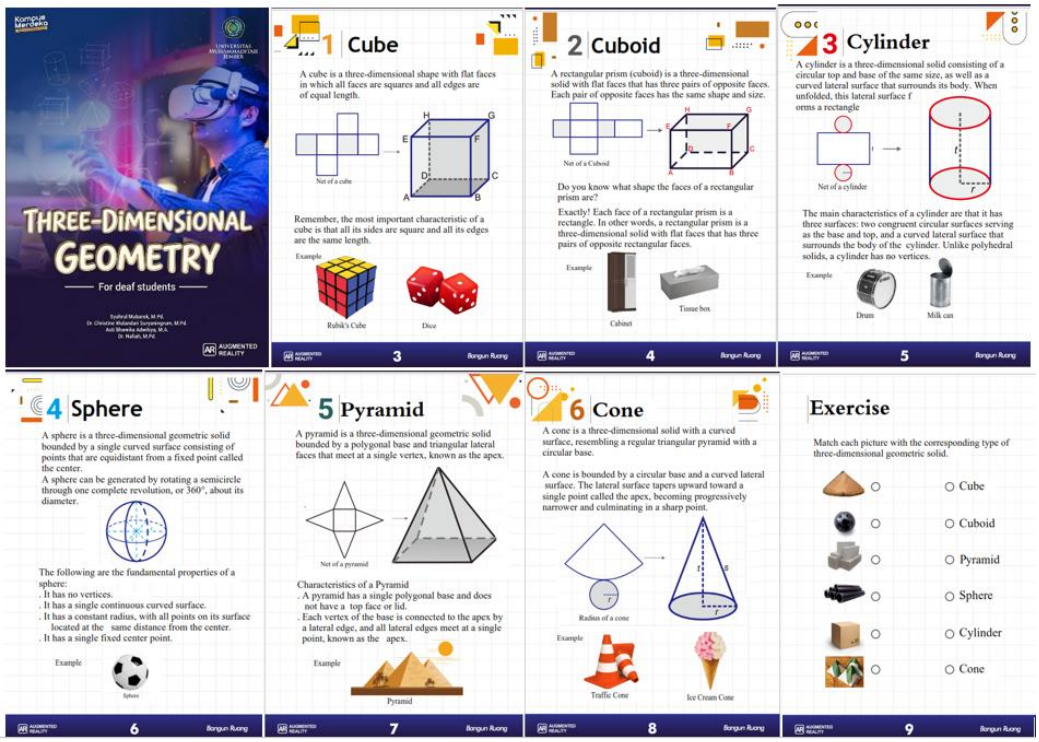


Figure 5. Final Product Development Result Design

3.1.4. Implementation

A small-scale trial was conducted at a special school in Jember Regency, involving seven deaf students. The purpose of this trial was to evaluate the effectiveness of the developed semiotics-based Augmented Reality (AR) learning media in enhancing students' understanding of three-dimensional geometric concepts (see Figure 6).



Figure 6. Trial activities

A small-scale trial conducted at the Branjangan State Special Needs School in Jember, involving seven deaf students, showed that students achieved an average comprehension score of 83.33%, which qualifies as Very Effective based on the effectiveness criteria presented in

Table 4. This finding provides initial evidence that the AR learning media developed improves the numeracy literacy of deaf students in three-dimensional geometry.

3.1.5. Evaluation

The evaluation phase focused on reflecting on the results of the small-scale trial and identifying aspects of the learning media that required further refinement before a large-scale trial. The evaluation was based on classroom observations, student comprehension scores, and teacher feedback collected during the small-scale trial. The results showed that students achieved an average comprehension score of 83.33%, which falls into the Very Effective category according to the effectiveness criteria presented in Table 4. Teachers also stated that the AR learning media increased student engagement and improved numeracy literacy in three-dimensional geometry material through semiotics-based AR media. Although the small-scale trial yielded Highly Effective results, the evaluation identified several areas for improvement, particularly regarding accessibility and adaptability in the classroom across a range of inclusive classroom environments. These findings were used to refine the semitok-based AR media, providing recommendations for future large-scale trials and effectiveness studies.

The success of the trial underscores the importance of inclusive approaches in education, enabling students with hearing disabilities to access and comprehend learning materials more effectively. The evaluation results demonstrated that the AR media met the required criteria and showed strong potential for enhancing students' literacy and numeracy in constructing mathematical concepts.

Although the outcomes were positive, this evaluation also provides a foundation for continuous improvement of the application and materials tested, with a focus on further enhancing students' understanding and engagement. If the Three-Dimensional Geometry application can be adapted for diverse learning contexts, it may offer valuable insights for broader educational implementation. Furthermore, the positive results provide a strong rationale for extending trials to larger groups of students or across different educational settings.

3.2. Discussion

Previous research on Augmented Reality (AR) has shown that AR can effectively support deaf students in understanding abstract geometric concepts by providing interactive three-dimensional visualizations, thereby enhancing conceptual understanding and learning outcomes (Andriyani et al., 2022). The semiotic perspective on AR emphasizes that visual signs, symbols, and student interactions play a central role in facilitating meaning-making in technology-enhanced learning environments (Lim & Lim, 2020; Wang & Tan, 2023). Consistent with previous research findings, the results of this study indicate that the semiotics-based AR learning media, developed as the Three-Dimensional Geometry application, is valid and practical for supporting mathematics learning for deaf students.

Preliminary analysis indicates that students struggle to grasp abstract three-dimensional geometric concepts. These findings suggest that visual representations play a crucial role in mathematics learning for deaf students, whose learning relies on visual

processing and visual-gestural communication (Healy et al., 2016; Santos & Cordes, 2022). From Piaget's perspective, concrete visual experiences can support learners in building conceptual understanding before moving on to more abstract reasoning. In line with Vygotsky's theory, Augmented Reality (AR) can serve as a form of instructional scaffolding by providing interactive three-dimensional visualizations that support learners in their Zone of Proximal Development (ZPD), thereby facilitating the transition from concrete experiences to abstract mathematical understanding (İslim et al., 2024; Srivastava et al., 2024). Therefore, AR technology serves as a bridge that expands learning opportunities for Deaf learners through meaningful and visually accessible mathematical experiences.

The Three-Dimensional Geometry pocketbook, used as a marker for the application, represents an implementation of Peirce's semiotic theory (1931–1958), which categorizes signs into icons, indices, and symbols (Suryaningrum et al., 2020). In this study, the 2D images within the book function as icons, the generated 3D objects serve as representations, and the meanings constructed by the students act as interpretants. This triadic relationship reinforces students with hearing impairments' understanding of geometry concepts through meaningful visual representations (Suryaningrum & Lestari, 2022).

The integration of Mayer's Cognitive Theory of Multimedia Learning and a semiotic perspective highlights the potential of multidimensional Augmented Reality (AR) learning for deaf students. Mayer (2024) explains that meaningful learning is enhanced when verbal information, visual representations, and interactive elements are integrated to support cognitive processing. Suarsana et al. (2021) demonstrated that multimedia learning developed in accordance with cognitive theory effectively supports mathematics learning in deaf students. From a semiotic perspective, technological and visual elements function as a sign system that facilitates meaning construction through learners' interactions with digital representations (Schiavetto & Schnaider, 2024; Schnaider, 2023). Previous research positions AR as a multimodal semiotic learning environment that supports deaf learners in constructing mathematical meaning through interactive visual representations.

The validation results for semiotic elements for deaf students, content, media, and language indicate that the Three-Dimensional Geometry application meets the criteria for content, technical, and linguistic feasibility. The learning materials are aligned with established educational standards, the interactive media is user-friendly, and the language employed effectively supports student comprehension. The expert validation process is consistent with the principles of multimedia instructional design, which emphasize formative evaluation throughout the development process to improve the quality and usability of learning media (Lee & Owens, 2004; Li & Sun, 2024). The relevance of the ADDIE model in inclusive media development is demonstrated in the design of an AR-based sign language learning tool (Mohd Ekhsan et al., 2022). Therefore, expert validation not only confirmed the application's suitability in terms of content and technical aspects but also highlighted its effectiveness in supporting numeracy learning for deaf students in an inclusive education context.

The expert validation of content, media, and language demonstrates that the Three-Dimensional Geometry application achieved a high level of feasibility. According to Kusasi et al. (2021), instructional media can be considered effective when they meet the criteria of content quality, linguistic accuracy, and technical presentation. These findings confirm that

the developed AR application fulfills the established standards of instructional media. The language validation results further indicate alignment with students' intellectual and socio-emotional development. This is particularly important since sign or visual language serves as the primary communication channel for students with hearing impairments. As emphasized in Alhazmi (2024), learning becomes more effective when information is presented in a balanced combination of visual and verbal modalities.

The overall expert validation score (91.2%) is comparable to previous research on AR-based mathematics learning media. Studies report validity scores ranging from approximately 88.57–95.23% (Alawiyah, 2024; Lestari et al., 2025; Sitompul et al., 2026). These findings indicate that the developed semiotics-based AR learning media meets quality standards for AR-based mathematics learning media. The integration of semiotic principles provides additional support by adapting visual representations and symbolic interactions to the learning characteristics of deaf students.

The small-scale trial, which yielded an average score of 83.33%, demonstrates the effectiveness of the AR-based learning media. This result supports prior research by Latif et al. (2024), who found that AR can enhance engagement, motivation, and conceptual understanding by providing interactive learning experiences. The findings are also consistent with Dual Coding Theory (Qasserras, 2024), which posits that information is more easily comprehended when processed through both visual and verbal channels. For deaf students whose verbal channel is limited, strengthening the visual channel through AR is an appropriate and effective solution.

A small-scale pilot implementation involved seven deaf students at a special school in Jember who met the inclusion criteria. Because the target population of deaf students at the junior high school level was limited, all eligible students were included in the pilot implementation. Larger-scale implementation is recommended for future studies to establish broader generalizability. The pilot implementation was intended to evaluate the usability, practicality, and initial feasibility of the developed learning media, not to obtain generalizable statistical findings. The results showed increased student interest and engagement during the learning process, as the AR application provided an interactive visual experience that supported the understanding of abstract three-dimensional geometric concepts. These findings are consistent with previous research showing that AR-based learning environments improve conceptual understanding, visualization, and learning engagement among students with special educational needs, including deaf students (Andriyani et al., 2022; Baragash et al., 2020; Henner et al., 2021).

Several challenges were identified during implementation. Some students initially required teacher assistance to operate the AR application and correctly position markers for object recognition. Differences in students' visual attention and prior mathematical knowledge resulted in varying levels of engagement with the application. Semiotic-based visual representations and interactive 3D models with concrete visual symbols could help students interpret abstract geometric concepts more effectively.

The results underscore the significance of semiotics in mathematics learning for deaf students, demonstrating how structured sign systems can strengthen conceptual understanding. The use of signs, symbols, and visual representations effectively facilitates the transition from

abstract to concrete reasoning, aligning with Peirce's semiotic theory, which emphasizes meaning-making through signs. When integrated with AR technology, this semiotic approach not only offers an innovative instructional framework but also enhances learners' engagement with mathematical content. Collectively, these findings suggest that combining semiotics with AR can create more accessible and cognitively supportive learning environments for deaf students.

Although the semiotic approach effectively supports the visualization of basic three-dimensional geometric concepts, some limitations remain. Concepts involving complex spatial transformations, cross-sections, and formal geometric proofs are difficult to represent through visual signs alone. Consequently, semiotic-based AR should be considered a complementary instructional approach, not a complete replacement for teacher explanations and guided learning activities.

The success of the Three-Dimensional Geometry AR media highlights the critical role of inclusive educational approaches in supporting diverse learners. This finding aligns with Alomari et al. (2023), who assert that every child, including those with special needs, is entitled to quality education enhanced by media designed to meet their unique learning requirements. Although the results of this study demonstrate high effectiveness, they also reveal substantial opportunities for refinement and further exploration. Future research could expand trials to larger, more diverse populations and integrate more adaptive and interactive features that better accommodate the specific learning needs of deaf students.

This study affirms that semiotics-based augmented reality (AR) media can function as an effective pedagogical tool for enhancing literacy and numeracy among deaf students. Semiotics-based AR learning media support mathematical literacy by helping deaf students interpret, visualize, and apply three-dimensional geometric concepts in meaningful learning contexts. Improving students' understanding of geometry is an important foundation for developing mathematical literacy, as geometry is a key domain within mathematical literacy. Through its interactive features, the application enables learners to visualize abstract mathematical symbols in concrete, virtual representations, thereby strengthening conceptual understanding. Such visualization not only facilitates deeper cognitive processing but also improves long-term retention of mathematical concepts. Overall, the findings highlight the potential of AR-integrated semiotic approaches to support more inclusive and accessible mathematics instruction.

This study has several limitations. First, the small-scale trial involved only seven deaf students from a special school in Jember, thus limiting the generalizability of the findings. Second, the effectiveness evaluation relied primarily on descriptive measures and classroom observations without comparison with a control group. Third, the study focused exclusively on three-dimensional geometry, so the findings cannot be generalized to other mathematics topics. Finally, although semiotics-based AR media effectively support visual learning, some abstract mathematical concepts still require teacher guidance and additional teaching strategies. Future studies should conduct larger-scale implementations with more diverse participants and more robust experimental designs.

4. CONCLUSION

This study demonstrates that semiotics-based Augmented Reality (AR) learning media is valid, practical, and effective in improving the literacy and numeracy skills of deaf students in three-dimensional geometry. By integrating semiotic principles with interactive AR technology, it provides meaningful visual representations to help students connect concrete experiences with abstract mathematical concepts. The findings suggest that combining semiotics with AR has the potential to support mathematical literacy through meaningful three-dimensional visualizations for deaf children.

This research is limited to expert validation and a pilot study involving a small number of participants. Therefore, future research should evaluate the developed media through larger-scale implementation and a more rigorous experimental design to obtain stronger evidence of its effectiveness. Researchers can also adapt semiotics-based AR designs to other mathematics topics, different educational levels, or other groups of learners with special educational needs. Furthermore, further studies could explore more qualitative data, such as classroom interactions and student learning experiences, to better understand how semiotic representations support mathematics learning at different educational levels.

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Declarations

Author Contribution	: CWS: Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing - original draft, and Writing - review & editing; AK: Formal analysis, Methodology, Supervision, Validation, and Writing - review & editing; SM: Investigation, Software, Visualization, and Writing - original draft; HS: Resources, Supervision, Validation, and Writing - review & editing.
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