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Enhancing numeracy learning among deaf students through BIMA: Design, development, and evaluation of an interactive mobile mathematical sign language application

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Abstract

Background: Deaf students often encounter challenges in numeracy learning because mathematics instruction is rarely supported by accessible digital media integrating sign language and interactive visual representations. This limitation highlights the need for inclusive mobile learning technologies that accommodate their communication and learning characteristics.
Aims: This study aimed to design, develop, and evaluate BIMA (Bahasa Isyarat Matematika), an interactive mobile mathematical sign language application, to enhance numeracy learning among deaf students.
Method: This study employed a Research and Development (R&D) approach using the ADDIE model. Data were collected through observations, interviews, expert validation questionnaires, user response questionnaires, and numeracy pre-test and post-test assessments. The data were analyzed using descriptive statistics and N-Gain analysis.
Results: The BIMA application achieved a valid level across mathematical content, sign language accuracy, media quality, practicality, and instructional effectiveness, with an overall validation score of 4.05. User responses were highly positive, reaching 96.6%, indicating excellent acceptance and usability. Students' mean numeracy scores increased from 56.47 to 84.12, with an N-Gain **of 0.64**, demonstrating a moderate improvement in numeracy achievement.
Conclusion: BIMA is a valid, practical, and effective mobile learning application that supports inclusive numeracy education by integrating mathematical sign language, interactive visualization, and mobile technology, offering an innovative approach to improving mathematics learning for deaf students.

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INTRODUCTION

Numeracy is a fundamental competency that enables individuals to understand, interpret, and apply mathematical concepts in various situations encountered in everyday life. Beyond performing arithmetic calculations, numeracy involves mathematical reasoning, problem-solving, critical thinking, and decision-making based on quantitative information (Asmara et al., 2026; Díez-Palomar et al., 2023; Reyna & Brainerd, 2023). The development of numeracy has become a central objective of contemporary education because it prepares learners to participate effectively in increasingly complex social and technological environments. Achieving strong numeracy skills is

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particularly important during basic education because this stage establishes the conceptual foundation for more advanced mathematical learning. However, not all students experience equal opportunities to develop these competencies due to differences in learning needs and educational accessibility. Deaf students often encounter additional challenges because mathematics instruction frequently relies on spoken language, verbal explanations, and written communication that may not fully accommodate their learning characteristics (Lenz et al., 2024; Ruiz-Cecilia et al., 2023; Uyen et al., 2021; Yore & Tang, 2022). These communication barriers make it difficult for many deaf learners to understand mathematical terminology, abstract concepts, and contextual problem-solving tasks (Krause & Wille, 2021; López-Leyton et al., 2026; Santos & Cordes, 2022). Consequently, mathematics learning for deaf students requires instructional approaches that prioritize visual communication, contextual representation, and accessible learning experiences. The integration of sign language into mathematics instruction provides an important bridge between mathematical concepts and students' preferred mode of communication. Therefore, developing innovative learning media that combine mathematics, sign language, and digital technology has become increasingly important for improving numeracy learning among deaf students.

Although considerable progress has been made in inclusive education, evidence from classroom practice indicates that many deaf students continue to experience low levels of numeracy achievement. Difficulties are particularly evident in understanding basic number concepts, performing arithmetic operations, and applying mathematical knowledge to solve practical problems (Barham, 2020; Lo, 2020). These learning challenges are closely related to the limited availability of instructional media specifically designed to address the visual and linguistic characteristics of deaf learners. Conventional teaching materials generally present mathematical concepts through text and oral explanations, reducing opportunities for meaningful conceptual understanding among students with hearing impairments (Güven et al., 2022; Kliziene et al., 2024). Recent developments in educational technology have created opportunities to design more accessible mathematics learning environments through multimedia and interactive applications. Visual representations, animation, interactive activities, and sign language demonstrations can support students in constructing mathematical meaning more effectively than traditional instructional approaches (Krause & Wille, 2021; Ziatdinov & James R. Valles, 2022). Such technological innovations also encourage greater student engagement because learning becomes more flexible, interactive, and learner-centered. In addition, mobile learning enables students to access educational content independently without being restricted by classroom time and location. These characteristics make mobile technology particularly suitable for supporting mathematics instruction within inclusive educational settings. Therefore, integrating mathematical content with sign language and mobile technology represents a promising strategy for reducing learning barriers experienced by deaf students.

To address these educational challenges, the BIMA (Bahasa Isyarat Matematika) application was developed as an interactive mobile learning platform specifically designed to support numeracy learning among deaf students. The application integrates mathematical sign language, visual learning materials, interactive exercises, and multimedia features into a single digital learning environment. Unlike conventional sign language applications that primarily facilitate communication, BIMA focuses on supporting conceptual understanding of mathematics through structured instructional activities. The application was designed to improve accessibility while encouraging independent learning and active student participation during mathematics instruction. Preliminary implementation demonstrated encouraging improvements in students' numeracy performance and positive responses from both teachers and learners. These findings indicate that integrating mathematical sign language with interactive mobile learning has considerable potential to strengthen mathematics learning for students with hearing impairments. Furthermore, the application has continued to evolve through systematic refinement to improve both its educational quality and technological functionality. The latest development includes additional interactive features that enhance students' learning experiences while increasing the practicality of classroom implementation. These improvements also support broader dissemination of the application across special education institutions and contribute to the advancement of accessible educational technology. Consequently, evaluating the educational effectiveness and implementation readiness of the enhanced BIMA application has become an important step toward promoting inclusive mathematics education.

Although previous studies have demonstrated that digital technologies and mobile learning positively contribute to mathematics education by improving students' achievement, motivation, and learning engagement (Alabdulaziz, 2021; Güler et al., 2022; Poçan et al., 2023; Viberg et al., 2023), these technologies have primarily been designed for general educational contexts rather than addressing the specific communication and learning characteristics of deaf students. Similarly, substantial advances have been achieved in sign language technologies through artificial intelligence, gesture recognition, wearable sensors, and deep learning to facilitate communication and sign language recognition (Kudrinko et al., 2021; Wen et al., 2021), yet these innovations rarely support mathematical concept learning or numeracy development. Within mathematics education, existing studies have emphasized inclusive pedagogical practices, language accessibility, and the role of sign language in facilitating mathematical understanding among deaf learners (Dessbesel et al., 2023; Gervasoni & Peter-Koop, 2020, 2020; Krause & Wille, 2021; Robertson & Graven, 2020), while research on assistive technologies has largely focused on improving communication, accessibility, and educational participation for students with disabilities rather than developing mathematics-specific instructional tools (Bell & Foiret, 2020; Rocha et al., 2023). Consequently, limited empirical evidence is available regarding an integrated mobile learning application that simultaneously combines mathematical sign language, interactive visual representation, gesture-based interaction, and numeracy instruction while being systematically evaluated in terms of validity, practicality, instructional effectiveness, and technology readiness within authentic special education settings. Therefore, this study addresses these gaps by designing, developing, and evaluating the BIMA (Bahasa Isyarat Matematika) application as an interactive mobile mathematical sign language platform to enhance numeracy learning among deaf students while providing empirical evidence that supports the advancement of inclusive mathematics education through accessible educational technology.

This study aimed to design, develop, and evaluate the BIMA (Bahasa Isyarat Matematika) application as an interactive mobile mathematical sign language learning platform to enhance numeracy learning among deaf students. The study employed a systematic research and development approach to ensure that the application addressed both instructional and technological requirements for inclusive mathematics education. The development process focused on integrating mathematical sign language, visual representation, multimedia learning resources, and interactive learning activities into a single mobile application. The study also evaluated the validity of the developed application through expert assessment involving specialists in mathematics education, educational technology, and sign language. Practicality was examined by analyzing users' responses following implementation in authentic special education settings. The effectiveness of the application was measured by comparing students' numeracy achievement before and after participating in learning activities using BIMA. In addition, the study assessed the technological readiness of the application to determine its feasibility for broader educational implementation. The findings are expected to provide empirical evidence regarding the educational value of integrating mathematical sign language with mobile learning technologies for deaf students. The study also seeks to contribute to the development of accessible instructional innovations that support equitable mathematics learning opportunities for students with hearing impairments. Ultimately, this research is intended to strengthen the implementation of inclusive mathematics education through evidence-based mobile learning technology that accommodates the communication and learning characteristics of deaf learners.

LITERATURE REVIEW

Numeracy is widely recognized as a multidimensional competency that extends beyond basic arithmetic skills to include mathematical reasoning, interpretation, communication, and the application of mathematical concepts in authentic situations. Contemporary mathematics education emphasizes numeracy as an essential foundation for lifelong learning because it enables individuals to solve problems, analyze quantitative information, and make evidence-based decisions. Within school settings, numeracy learning encourages students to connect mathematical concepts with meaningful experiences rather than memorizing isolated computational procedures. Effective numeracy instruction therefore requires learning environments that actively promote conceptual understanding, critical thinking, and mathematical communication. In inclusive education, these instructional principles become increasingly important because students possess diverse cognitive, linguistic, and sensory characteristics that influence their learning processes (Ugalde et al., 2021). Educational equity requires mathematics instruction to be adapted so that every learner can access mathematical knowledge regardless of disability or communication differences. Deaf students often require instructional approaches that emphasize visual communication, contextual learning, and multimodal representation because spoken explanations alone cannot adequately support mathematical understanding. Consequently, inclusive mathematics education promotes the integration of accessible instructional strategies that accommodate learners' individual needs while maintaining equivalent learning objectives. Recent educational reforms increasingly recognize that technology-assisted instruction can contribute significantly to improving equitable access to mathematics learning for students with disabilities. Therefore, strengthening numeracy learning among deaf students requires instructional innovations that integrate accessibility, pedagogy, and digital technology within a comprehensive learning environment.

Sign language serves not only as a communication system but also as an important cognitive tool that supports knowledge construction among deaf learners. Within mathematics education, mathematical sign language enables abstract concepts, symbols, and procedures to be communicated through meaningful visual-spatial representations (Gürefe, 2025; Krause & Wille, 2021; Özlav & Akıncı, 2024). The availability of standardized mathematical signs contributes to clearer conceptual explanations and reduces ambiguity during classroom instruction. Mathematical sign language also facilitates interactions between teachers and students by creating a common language for discussing mathematical ideas. Research has demonstrated that students who receive mathematics instruction supported by sign language generally exhibit stronger conceptual understanding than those relying primarily on written explanations (Gürefe, 2026; Santos & Cordes, 2022; Sortino et al., 2026). Furthermore, visual-spatial communication aligns closely with the cognitive characteristics of many deaf learners, enabling more efficient processing of mathematical information (Thom & Hallenbeck, 2022; Zahid Abdush Shomad, 2026). Despite these educational advantages, mathematical sign language resources remain limited in many educational contexts, particularly within digital learning environments. Existing sign language applications frequently emphasize everyday communication instead of mathematics-specific terminology and instructional content. Consequently, teachers often experience difficulties in providing consistent mathematical explanations using accessible visual language. Developing digital applications that systematically integrate mathematical sign language into mathematics instruction therefore represents an important direction for advancing inclusive mathematics education.

Mobile learning has become one of the most influential technological innovations in contemporary education because it provides flexible, accessible, and learner-centered learning experiences. The widespread availability of smartphones and tablet devices enables students to access educational resources beyond conventional classroom settings. Interactive mobile applications incorporate multimedia components such as animation, video, simulation, visualization, and immediate feedback that facilitate deeper conceptual understanding (Md Sabri et al., 2024; Staneviciene & Žekienė, 2025). In mathematics education, these features enable abstract concepts to be presented through dynamic visual representations that improve students' engagement and comprehension. Mobile learning also encourages self-paced learning because students can review instructional materials repeatedly according to their individual learning needs. For students with disabilities, mobile technologies offer additional accessibility features that support independent learning and reduce barriers associated with traditional instructional methods. Interactive educational technologies further enhance motivation by creating engaging learning environments that encourage exploration and active participation. Studies have consistently reported positive relationships between mobile learning implementation and improvements in mathematics achievement, learning motivation, and student engagement (Ali et al., 2023; Güler et al., 2022; Poçan et al., 2023; Tang et al., 2023). Nevertheless, relatively few mobile applications have been specifically developed to integrate mathematical instruction with sign language and visual accessibility for deaf learners. This limitation highlights the importance of developing specialized mobile learning applications that address both educational effectiveness and accessibility within inclusive mathematics education.

Assistive technology plays an essential role in promoting educational accessibility by enabling students with disabilities to participate more effectively in learning activities. Advances in digital technology have significantly expanded the range of assistive tools available for supporting communication, learning, and classroom participation among deaf students. Recent innovations include artificial intelligence, gesture recognition, computer vision, wearable sensors, and multimedia learning systems that facilitate more accessible educational experiences (Ahmed et al., 2025; Almufarreh & Arshad, 2023; Hong et al., 2025; Parveen et al., 2026). Most existing assistive technologies, however, have been developed primarily to improve communication rather than to support mathematics learning specifically. Mathematics education requires specialized instructional support because mathematical language contains abstract symbols, logical relationships, and conceptual structures that differ from everyday communication (Hultdin et al., 2023; Maanu & Asare, 2025). Consequently, mathematics-specific assistive technologies should integrate conceptual explanations, visual representations, interactive learning activities, and mathematical sign language within a unified instructional framework. Such integration enables students to connect mathematical symbols with meaningful visual experiences that enhance conceptual understanding. Furthermore, assistive technologies designed specifically for mathematics education can reduce dependence on teacher explanations by promoting greater learner autonomy. Educational innovations that combine accessibility with instructional effectiveness therefore have considerable potential to improve mathematics learning outcomes among deaf students. These developments provide a theoretical foundation for designing interactive mobile applications that support inclusive numeracy learning through accessible educational technology.

The development of BIMA is grounded in the integration of inclusive education, multimedia learning, mobile learning, and mathematical sign language to create an accessible mathematics learning environment for deaf students. From the perspective of inclusive education, learning technologies should eliminate barriers that prevent students with disabilities from accessing equivalent educational opportunities. Multimedia learning theory suggests that students achieve deeper understanding when verbal and visual information are presented in complementary formats that reduce unnecessary cognitive load. For deaf learners, visual communication becomes the primary channel through which mathematical concepts are acquired, making interactive multimedia particularly appropriate for mathematics instruction (Krause & Wille, 2021; Videla & Abrahamson, 2026). Mobile learning further strengthens this instructional approach by enabling flexible access to learning resources regardless of time and place. The integration of mathematical sign language with interactive visual representations facilitates conceptual understanding by connecting mathematical symbols with meaningful visual communication. Interactive exercises and immediate feedback also promote active learning while supporting students' independent exploration of mathematical concepts. The combination of these theoretical perspectives provides a comprehensive framework for designing accessible educational technologies that address both pedagogical and technological dimensions of inclusive mathematics education. Accordingly, BIMA represents an instructional innovation that integrates these complementary theoretical principles into a single interactive mobile learning application. The present study therefore evaluates the validity, practicality, effectiveness, and implementation readiness of the BIMA application for enhancing numeracy learning among deaf students.

METHOD

Research Design

This study employed a Research and Development (R&D) approach using the ADDIE instructional design model, which consists of five sequential phases: Analysis, Design, Development, Implementation, and Evaluation. The ADDIE model was selected because it provides a systematic, iterative, and learner-centered framework for developing educational technology while ensuring continuous improvement throughout the development process. The model is particularly appropriate for interactive mobile learning applications because it integrates instructional design, multimedia development, implementation, and evaluation into a unified framework. During the analysis phase, the learning needs of deaf students were identified through classroom observations, interviews with teachers, and a review of mathematics learning challenges encountered in special education settings. The design phase focused on developing instructional objectives, mathematical sign language content, interface layouts, and interactive learning activities according to inclusive instructional principles. Subsequently, the development phase involved constructing the BIMA application by integrating mathematical sign language, multimedia resources, visual representations, and interactive learning features into an Android-based mobile learning platform. The implementation phase consisted of classroom trials conducted in special schools for deaf students to evaluate the application's educational performance under authentic learning conditions. Finally, the evaluation phase examined the validity, practicality, effectiveness, and technology readiness of the application through expert assessment, user responses, and students' numeracy learning outcomes. This systematic approach ensured that both pedagogical and technological considerations were incorporated throughout the development process, resulting in an accessible mobile learning application designed to support inclusive numeracy education.

Participants

The participants were selected purposively according to their direct involvement in mathematics instruction and special education practices. The expert validation stage involved 33 participants, consisting of mathematics teachers and special education practitioners, who evaluated the mathematical content, sign language accuracy, instructional quality, media design, and usability of the BIMA application. The implementation and effectiveness testing stage involved 78 deaf students enrolled in six special schools (Sekolah Luar Biasa/SLB). In addition, 83 teachers and special education practitioners participated in evaluating the application's practicality and implementation feasibility during classroom activities. Consequently, the field implementation involved a total of 161 participants representing both end users and educational practitioners. The participating schools represented authentic inclusive learning environments where the application could be evaluated under real instructional conditions. The distribution of participants across the participating schools is presented in Table 1.

Table 1. Validation and Response Testing Participants

Schools	Deaf Students	Teachers/Practitioners
SLBN Kandat	12	16
SLB Bhakti Mulya Kandat	18	10
SLB Kanigoro Kras	8	13
SLB Nurul Ikhsan Ngadiluwih	10	15
SLB Bhakti Pemuda Tamanan	8	14
SLB Dharma Wanita Grogol	12	15
Total	**78**	**83**
Overall Participants		**161**

Instruments and Data Collection

Multiple research instruments were employed to evaluate the educational quality and implementation readiness of the BIMA application. Classroom observations and semi-structured interviews were conducted during the needs analysis stage to identify challenges experienced by deaf students and teachers in numeracy learning. Expert validation questionnaires were used to assess mathematical content, sign language appropriateness, instructional design, interface quality, media functionality, and overall product feasibility. The expert validation instrument was adapted from previous educational media evaluation studies to ensure the comprehensive assessment of instructional quality. Functional testing was also conducted to verify that every application feature operated according to its intended instructional purpose. User response questionnaires were administered to teachers, practitioners, and students after classroom implementation to evaluate usability, accessibility, learning satisfaction, and perceived instructional benefits. The effectiveness of the application was measured using numeracy pre-test and post-test instruments administered before and after students participated in learning activities using BIMA. Furthermore, construct validation was conducted using Gregory's validation procedure to determine the level of agreement among expert validators. Documentation of implementation activities and product dissemination was also collected to support the assessment of technology readiness for broader educational implementation.

Data Analysis

The collected data were analyzed using descriptive and quantitative statistical techniques. Expert validation scores were analyzed by calculating mean values and categorizing the results according to predetermined validity criteria. Functional validation results were summarized using percentage analysis to determine the operational feasibility of the developed application. Gregory's validity coefficient was employed to evaluate construct validity by measuring the level of agreement between expert validators regarding the quality of the application. User response questionnaire data were analyzed descriptively using percentage values to determine the practicality and acceptance of the application among teachers, practitioners, and students.

Students' numeracy achievement was analyzed by comparing pre-test and post-test scores. Learning improvement was calculated using the Normalized Gain (N-Gain) index to determine the effectiveness of the BIMA application in enhancing students' numeracy learning. All quantitative analyses were conducted using IBM SPSS Statistics, while qualitative findings obtained through observations and interviews were used to support the interpretation of quantitative results.

Research Procedure

The research procedure followed the five phases of the ADDIE instructional design model while simultaneously supporting the advancement of the BIMA application toward Technology Readiness Level (TRL) 6. During the initial implementation in 2024, the BIMA Dictionary was developed as a website-based prototype and evaluated in a limited educational environment, achieving TRL 4. In 2025, the prototype was transformed into an Android-based application and publicly tested in two special schools, enabling the product to reach TRL 5. The final development stage in 2026 focused on integrating motion sensor technology, improving application functionality, and conducting broader implementation across six special schools. Throughout this phase, expert validation, classroom implementation, user evaluation, and dissemination activities were conducted to examine the educational quality and implementation readiness of the developed application. The TRL assessment included prototype feasibility evaluation, preparation of implementation recommendations, communication with educational partners, product dissemination, and verification of product acceptance by participating institutions. These activities confirmed that the BIMA application successfully achieved TRL 6, indicating that the developed product had been validated and demonstrated in authentic educational environments. The complete development pathway of the BIMA application from TRL 4 to TRL 6 is illustrated in Figure 1.

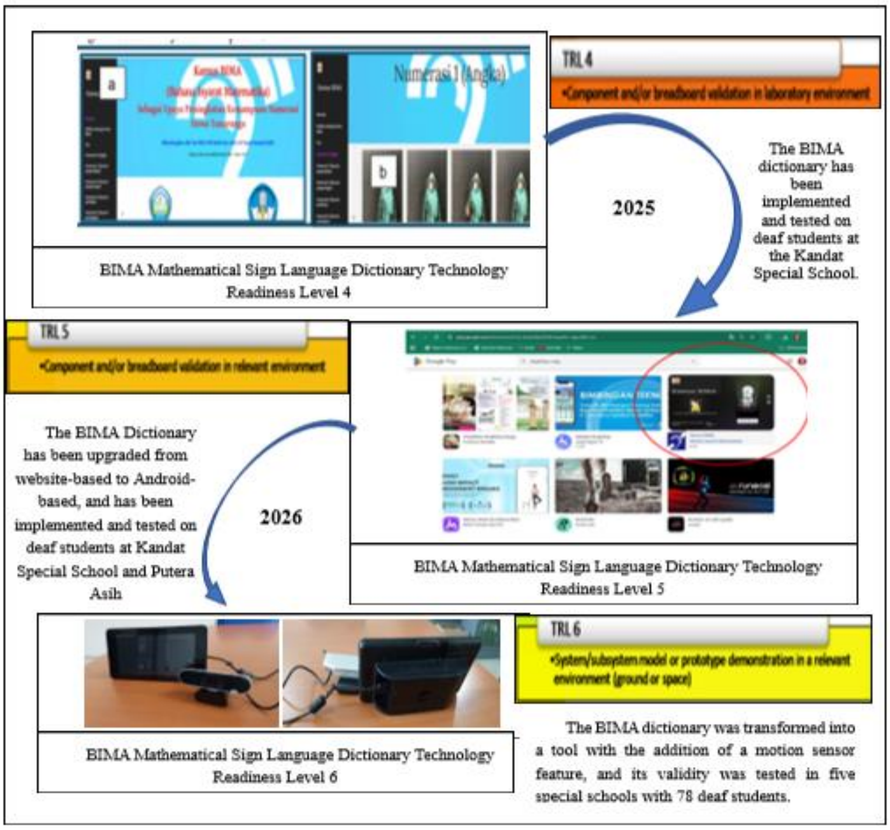

Figure 1. Improving the Technology Readiness Level of the BIMA Mathematical Sign Language Dictionary

RESULTS AND DISCUSSION

Results

The Outputs of The Development Analysis

The BIMA Dictionary product in the form of a device with an additional motion sensor for numeracy learning for deaf students.

Several feature changes were made in the development of the BIMA Dictionary to achieve TRL 6. These changes include: a) changing the application base used from website-based to Android-based and sensor tools; b) addition of motion sensor features and monitors that can represent motion as mathematical symbols; c) addition of numerical access to 2D material features in the form of sign language videos on numeracy topics, consisting of: numeracy 1 (numbers), numeracy 2 (addition), numeracy 3 (subtraction), numeracy 4 (multiplication), and numeracy 5 (division); d) and program transformation in the form of digital demonstration tools with casing modifications.

(a) (b)

Figure 2. BIMA Dictionary Feature Development ((a) before, and (b) after)

Results of the validity analysis of the BIMA Dictionary product by experts.

Based on expert validation on functional aspects, the BIMA Dictionary application demonstrated a high level of functional suitability. Of the 33 test items, 32 were declared valid and 1 item was declared invalid. The invalid item was in the Practice menu, namely the Start Quiz function, because the quiz did not appear according to the test target. All items in the Material, Instructions, and About menu were declared valid. Overall, the application's functional validation reached 96.97%.

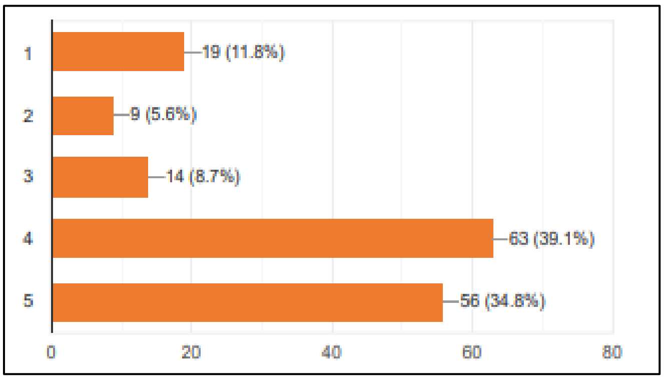

Figure 3. The Development of The BIMA Dictionary Feature Works Well, Is Practical, and is Easy to Use.

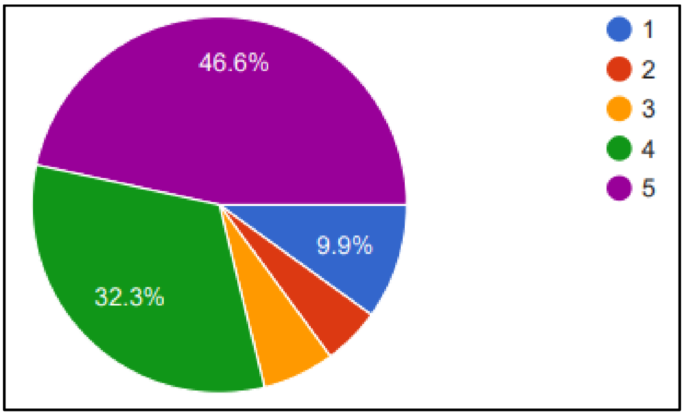

Figure 4. BIMA Dictionary as A Medium for Implementing Numeracy Practices for Deaf Students

Results of user response analysis as evidence of the BIMA Dictionary public testing at five special schools with 161 users. These results confirm that the BIMA Dictionary's technological readiness has reached TRL 6. Analysis of responses from 161 users showed that the BIMA Dictionary prototype received consistently positive feedback across design, content, and usability/benefit aspects. The most prominent pattern was the predominance of responses with scores of 4 and 5 across nearly all items. This indicates that users consider the app not only usable but also relevant for supporting learning.

A key finding lies in the content aspect, which emerged as the product's primary strength. The three most prominent indicators were the presentation of the material that supports learning (80.8%), ease of understanding of the material (80.1%), and the accuracy of the concepts, facts, and procedures within the material, which were rated as good (80.1%). At the same time, the design aspect also showed a positive trend, particularly in terms of feature support for learning (78.9%), text readability (78.3%), and image clarity (78.3%). However, these results also revealed relatively weak points, button functionality (70.2%). Thus, the results of user responses confirm that the main strength of the BIMA Dictionary lies in the substance of the material and learning support, while aspects that still require strengthening are the technical and operational accessibility of the application.

The results of the BIMA Dictionary product construct validation analysis.

The results of the BIMA Dictionary product construct validation analysis were conducted by grouping the assessment results of the two validators into a cross-tabulation according to Gregory's procedure, then calculating the validity coefficient. This coefficient indicates the level of agreement between validators regarding the feasibility of the developed media. The closer the value is to 1, the higher the level of validity of the media. The interpretation criteria for Gregory validity coefficient results used in this study are presented in the following Table 2.

Table 2. Validation Results matrix

Matrix Gregory's procedure		Expert I	
		Less Relevant (Score 1-2)	Relevant (Score 3-5)
Expert II	Less Relevant (Score 1-2)	A = 0	B = 1
	Relevant (Score 3-5)	C = 0	D = 10

Validity Coefficient Value = $\frac{D}{A+B+C+D} = \frac{10}{11} = 0.901$
(The coefficient range of 0.80 – 1.00 is very valid).

The results of the social impact analysis on the numeracy skills of students with hearing impairments. BIMA Dictionary shows a significant positive social impact by enhancing the numeracy skills of deaf students. Empirical findings indicate that students' numeracy abilities increased by 38% after the implementation of the BIMA Dictionary, particularly in supporting their understanding of mathematical concepts through visual and interactive approaches.

The outputs of product dissemination

The BIMA Dictionary is an appropriate technology that has been accepted by a partner, a special needs school, as a prototype testing site. This is evidenced by the handover letter from the partner.

(a) (b)

Figure 5. Documentation of The Handover Letter for BIMA Dictionary Products by Partners ((a) SLB Dharma Wanita Grogol, and (b) SLBN Kandat)

Discussion

The findings demonstrate that the development of the BIMA application represents a significant advancement in inclusive mathematics education by transforming an early web-based prototype into a more comprehensive Android-based learning system equipped with interactive and assistive features. This technological transformation substantially improves learning accessibility because mobile platforms allow students to access instructional materials more flexibly across various learning environments while promoting greater learning independence. The integration of mobile technology is particularly important for deaf students because their learning process relies heavily on continuous access to visual instructional resources that can be revisited according to individual learning needs (Farhan & Razmak, 2022; Gehret & Elliot, 2025; Hurtado-Sánchez et al., 2026; Zhang et al., 2024). Unlike conventional classroom instruction, mobile learning environments provide opportunities for repeated exploration of mathematical concepts without limitations imposed by instructional time or teacher availability. Such flexibility enables students to develop mathematical understanding through self-paced learning that accommodates individual differences in cognitive processing. Furthermore, the successful transformation of BIMA into a more functional mobile application demonstrates that technological innovation can be effectively integrated with inclusive instructional principles to reduce learning barriers experienced by students with hearing impairments. The achievement of Technology Readiness Level 6 also indicates that the application has progressed beyond conceptual development and laboratory validation toward successful implementation in authentic educational settings. Educational technologies that reach implementation readiness possess greater potential for sustainable adoption because they have demonstrated feasibility under real classroom conditions. These findings therefore suggest that the educational contribution of BIMA extends beyond software development by providing an accessible instructional ecosystem capable of supporting mathematics learning in inclusive educational environments. Overall, the transition from a conventional prototype to an implementation-ready mobile learning application demonstrates how educational technology can simultaneously improve accessibility, instructional quality, and learning opportunities for deaf students.

One of the most important innovations introduced by the BIMA application is the integration of motion sensor technology, which enables mathematical concepts to be represented through meaningful physical movement rather than relying exclusively on verbal explanations. This approach reflects the principles of embodied and multimodal learning, which emphasize that conceptual understanding becomes stronger when learners actively connect abstract knowledge with physical and visual experiences. For deaf students, visual-spatial processing constitutes the primary pathway for acquiring new knowledge because spoken language provides limited support during mathematics instruction (Bower et al., 2020; Gordon et al., 2021; Li et al., 2023; Peng et al., 2020). Consequently, presenting mathematical concepts through gesture-based interaction allows students to construct conceptual understanding more naturally than traditional text-dominated instructional approaches. The motion sensor feature therefore functions not merely as a technological addition but as a pedagogical strategy that bridges symbolic mathematical representations with concrete learning experiences. This instructional design encourages students to participate actively during learning activities because they interact directly with mathematical concepts rather than passively observing demonstrations. Active engagement also contributes to deeper conceptual processing by encouraging students to integrate visual information, physical movement, and mathematical reasoning simultaneously. Such multimodal interaction is particularly valuable in mathematics education because abstract concepts often become difficult to understand when presented through a single communication modality. The findings therefore reinforce the argument that effective mathematics instruction for deaf learners should combine interactive technology with pedagogical approaches that accommodate visual and kinesthetic learning preferences. Consequently, integrating motion-based interaction into mobile mathematics learning represents a meaningful innovation that contributes to more inclusive and conceptually rich numeracy instruction.

Another important contribution of the BIMA application lies in the integration of mathematical sign language within structured multimedia learning resources designed specifically for numeracy instruction. Mathematical sign language functions not only as a communication medium but also as a cognitive tool that enables students to organize, interpret, and communicate mathematical ideas through visual-spatial representations. The inclusion of structured sign language videos covering numbers and basic arithmetic operations significantly strengthens linguistic accessibility by reducing dependence on written explanations that may be difficult for many deaf learners to understand. Through this approach, students can establish stronger relationships between mathematical symbols, visual demonstrations, and conceptual meanings during learning activities. Interactive multimedia further enhances this process because visual explanations, animations, and repeated demonstrations enable students to revisit difficult concepts until meaningful understanding is achieved (Desai & Kulkarni, 2022; Lin et al., 2022; Rahmawati et al., 2022). Such learning experiences are consistent with multimedia instructional principles that emphasize the complementary roles of visual representation and learner interaction in facilitating conceptual development. Unlike many existing sign language applications that primarily emphasize communication skills, the BIMA application intentionally integrates mathematical sign language into structured instructional sequences designed to improve numeracy learning. This distinction represents an important pedagogical contribution because it demonstrates that assistive technologies can function not only as accessibility tools but also as effective mathematics learning media. The combination of mathematical sign language, interactive multimedia, and mobile accessibility therefore creates a comprehensive learning environment that supports both conceptual understanding and active student engagement (Cosentino & Giannakos, 2023; Errabo & Ongoco, 2024; Md Sabri et al., 2024; Muir et al., 2022; Staneviciene & Žekienė, 2025). Overall, these findings indicate that integrating visual communication with mathematics-specific instructional design provides a promising direction for strengthening inclusive numeracy education and improving learning opportunities for deaf students.

The results of this study further demonstrate that the BIMA application achieved a high level of validity, practicality, and educational feasibility, indicating that the developed application satisfies both instructional and technological quality standards. The high expert validation score suggests that the mathematical content, sign language accuracy, interface design, and learning activities have been successfully integrated into a coherent instructional system that supports numeracy learning (Abrahamson et al., 2020; Kim et al., 2025; Utami et al., 2024). Such comprehensive validation is essential because educational technology should not only function technically but also align with curriculum objectives, learner characteristics, and instructional principles. The excellent level of functional suitability further indicates that the application operates according to its intended design and provides reliable support for mathematics instruction in authentic learning environments. Construct validation also demonstrates strong agreement among experts regarding the educational appropriateness of the developed application, suggesting that the instructional components effectively represent the intended learning objectives. High construct validity is particularly important because it ensures that learning media accurately measure and facilitate the competencies they are designed to develop. In addition, the positive responses obtained from teachers, practitioners, and students indicate that the application possesses a high degree of usability and acceptance during classroom implementation. Educational technologies that are perceived as useful, accessible, and easy to operate are generally more likely to be adopted consistently within instructional practice because they reduce implementation barriers for both teachers and learners. These findings therefore confirm that the success of digital learning innovations depends not only on technological sophistication but also on their ability to satisfy pedagogical, functional, and user-centered requirements simultaneously. Overall, the combination of expert validation, functional testing, construct validation, and positive user responses provides strong empirical evidence supporting the educational quality and implementation feasibility of the BIMA application.

The most significant outcome of this study is the substantial improvement in students' numeracy achievement following the implementation of the BIMA application, indicating that integrating mathematical sign language with interactive mobile learning can effectively facilitate conceptual understanding among deaf students. The observed improvement suggests that students benefited from instructional experiences that simultaneously combined visual representation, interactive activities, and accessible communication throughout the learning process. Rather than relying solely on memorization of arithmetic procedures, students were encouraged to develop meaningful conceptual understanding through repeated interaction with mathematical symbols, sign language demonstrations, and multimedia explanations. This instructional process is likely to strengthen students' mathematical reasoning because visual communication reduces language-related obstacles that frequently interfere with conceptual learning among deaf learners. The findings further indicate that combining accessible educational technology with inclusive instructional strategies creates learning experiences that are more engaging, meaningful, and responsive to students' individual learning characteristics. Although the application demonstrated strong educational performance, the evaluation also identified several aspects that require further refinement, particularly regarding interface navigation and button functionality. Continuous improvement of these technical features is necessary because interface usability directly influences learners' interaction efficiency, satisfaction, and overall learning experience. Future development should therefore prioritize improvements in user interface responsiveness, personalization features, adaptive learning pathways, and expanded mathematical content to increase the instructional value of the application (Dritsas & Trigka, 2025; Song et al., 2024). Broader implementation involving more diverse educational contexts and larger participant populations would also provide stronger evidence regarding the generalizability and long-term effectiveness of the developed application.

Collectively, these findings demonstrate that the BIMA application represents a valid, practical, and effective educational innovation that contributes to advancing inclusive mathematics education while expanding opportunities for deaf students to develop meaningful numeracy competencies through accessible mobile learning technologies.

Implications

The findings of this study provide important theoretical and practical implications for the advancement of inclusive mathematics education through the integration of accessible educational technology. From a theoretical perspective, this study extends the current body of knowledge by demonstrating that the integration of mathematical sign language, interactive multimedia, and mobile learning can establish an effective instructional framework for enhancing numeracy learning among deaf students. The study also reinforces the view that assistive technology should function not merely as a communication aid but as a pedagogically meaningful learning medium capable of supporting conceptual understanding and mathematical reasoning. Furthermore, the successful implementation of the BIMA application highlights the importance of combining visual-spatial learning principles with inclusive instructional design to accommodate the cognitive and linguistic characteristics of learners with hearing impairments. From a practical perspective, the developed application provides mathematics teachers and special education practitioners with an accessible instructional resource that can enrich classroom learning while promoting greater student engagement and independent learning. The integration of mathematical sign language and interactive learning activities also offers an alternative instructional strategy for reducing communication barriers that frequently hinder mathematics learning among deaf students. In addition, the achievement of Technology Readiness Level 6 indicates that the application possesses sufficient implementation readiness to support broader adoption across special education institutions and inclusive learning environments. The findings further encourage educational institutions and policymakers to invest in the development of mathematics-specific assistive technologies that are evidence-based, curriculum-aligned, and responsive to the learning needs of students with disabilities. This study also provides practical guidance for educational technology developers by emphasizing the importance of integrating accessibility, pedagogical quality, usability, and user-centered design within a single instructional platform. Beyond the context of deaf education, the instructional principles underlying the BIMA application may serve as a reference for designing inclusive mobile learning technologies for other groups of learners with diverse educational needs. Moreover, the integration of mathematical sign language, visual representation, and interactive mobile technology offers a scalable instructional model that can support the broader digital transformation of inclusive mathematics education. Overall, this study contributes a comprehensive framework for developing, evaluating, and implementing accessible mobile learning applications that strengthen numeracy learning while promoting equitable educational opportunities for deaf students through technology-enhanced mathematics instruction.

Limitations and Suggestions for Future Research

This study has several limitations that should be considered when interpreting the findings and planning future investigations. First, the implementation of the BIMA application was conducted in only six special schools involving a relatively limited number of deaf students, which may restrict the generalizability of the findings to broader educational contexts. Second, the evaluation focused primarily on fundamental numeracy learning, including number concepts and basic arithmetic operations, without examining more advanced mathematical topics that require higher-order mathematical reasoning. Third, the effectiveness assessment was conducted over a relatively short implementation period, making it difficult to determine the long-term impact of the application on students' mathematical achievement, conceptual retention, and independent learning habits. Fourth, although the application successfully integrated mathematical sign language, interactive multimedia, and motion sensor technology, the study did not investigate differences in learning outcomes associated with students' individual characteristics, such as age, prior mathematical ability, sign language proficiency, or digital literacy. In addition, the current version of the application provides standardized instructional pathways and has not yet incorporated adaptive learning features capable of automatically adjusting content difficulty according to students' learning progress. Future studies are therefore encouraged to involve larger and more diverse participant populations across different educational regions to improve the external validity and generalizability of the findings. Further research should also evaluate the effectiveness of the application in teaching more complex mathematical domains, including geometry, fractions, algebra, and mathematical problem-solving. Longitudinal studies are recommended to investigate the sustained effects of the application on conceptual understanding, numeracy development, learning motivation, and academic achievement over extended periods. Moreover, future research should integrate intelligent technologies, such as artificial intelligence, adaptive learning algorithms, and learning analytics, to provide personalized instructional support and real-time feedback based on individual learner performance. Comparative studies involving different assistive learning technologies and instructional models would also provide a deeper understanding of the relative effectiveness of various approaches for improving mathematics learning among deaf students. Overall, addressing these limitations will contribute to the continuous refinement of accessible educational technology while strengthening the evidence base for integrating mobile mathematical sign language applications into inclusive mathematics education.

CONCLUSION

This study successfully designed, developed, and evaluated the BIMA (Bahasa Isyarat Matematika) application as an interactive mobile mathematical sign language learning platform to enhance numeracy learning among deaf students. The development process resulted in an innovative educational application integrating mathematical sign language, motion sensor technology, interactive multimedia, and visual representations to create an accessible learning environment tailored to the communication characteristics of students with hearing impairments. The expert validation results confirmed that the application achieved a high level of validity in terms of instructional design, mathematical content, sign language accuracy, media quality, and construct validity, demonstrating its suitability for educational implementation. The positive evaluations obtained from teachers, special education practitioners, and students further indicate that the application is practical, user-friendly, visually engaging, and responsive to users' instructional needs. The successful implementation across six special schools and the achievement of Technology Readiness Level (TRL) 6 demonstrate that the application has progressed beyond prototype development and has proven its feasibility in authentic educational settings. Furthermore, the significant improvement in students' numeracy achievement indicates that integrating mathematical sign language with interactive mobile learning effectively facilitates conceptual understanding and mathematical learning among deaf students. These findings confirm that combining accessible instructional design with assistive technology can substantially reduce communication barriers that frequently hinder mathematics learning for students with hearing impairments. The study also demonstrates that mathematical sign language serves not only as a communication medium but also as an effective instructional resource that strengthens conceptual understanding through visual-spatial learning experiences. Beyond its educational effectiveness, the BIMA application provides an evidence-based model for integrating inclusive pedagogy, digital technology, and mathematics instruction within a single learning platform. The successful dissemination of the application through institutional adoption and technology development initiatives further indicates its strong potential for sustainability and broader implementation in special education. Consequently, this study contributes to the growing body of knowledge on inclusive mathematics education by providing empirical evidence that accessible mobile learning technologies can improve numeracy learning while promoting equitable educational opportunities for deaf learners. Overall, the BIMA application represents a valid, practical, effective, and implementation-ready educational innovation that offers a comprehensive framework for advancing inclusive numeracy education through technology-enhanced mathematics learning.

AUTHOR CONTRIBUTIONS STATEMENT

Ika Santia contributed to the conceptualization of the study, research design, development of the BIMA application, supervision of the development process, data interpretation, and manuscript drafting. Muhammad Najibulloh Muzaki contributed to the application development, instrument development, data collection, classroom implementation, data analysis, and preparation of the initial manuscript. Aprilia Dwi Handayani contributed to the validation of instructional content, evaluation of mathematical sign language materials, interpretation of the findings, and critical revision of the manuscript. Wasilatul Murtafiah contributed to the methodological supervision, validation of the research design and instruments, interpretation of the results, and critical review and editing of the manuscript. All authors participated in reviewing the manuscript, approved the final version for publication, and agreed to be accountable for all aspects of the work.

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