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A Multimodal Machine Learning-Based Assistive Communication App for Impaired Children Using TensorFlow Lite

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Abstract

This study presents the development and evaluation of a mobile-based multimodal assistive communication application designed to enhance communication for impaired children. The application integrates gesture recognition, facial expression analysis, customizable communication buttons, language video tutorials, and text-to-speech functionality to facilitate real-time, interactive communication. The research employed a user-centered design methodology, including online surveys, focus group discussions, and iterative prototype testing with 15 participants, comprising children, caregivers, and professionals. A comprehensive Software Requirements Specification (SRS) guided the development, ensuring alignment with user needs and practical usability in both home and educational settings. System evaluation was conducted following the ISO/IEC 25010:2023 software quality framework, emphasizing six attributes: functional suitability, performance efficiency, interaction capability, usability, compatibility, and portability. Findings revealed strong agreement across all evaluated criteria, with an overall weighted mean of 4.57. The application demonstrated high adaptability to user preferences, consistent performance across devices, reliable real-time interaction, and an intuitive interface suitable for users with varying digital literacy. Caregivers and professionals reported that the system effectively supports communication in dynamic, real-world scenarios, reduces frustration, and strengthens social and educational engagement for impaired children. Based on these outcomes, it is recommended to further enhance responsiveness and contextual accuracy, expand multilingual and culturally relevant features, and improve integration with third-party assistive technologies. Structured training programs for caregivers and longitudinal evaluations are also advised to optimize adoption and measure long-term impact. Overall, the system offers a scalable, accessible, and inclusive tool that addresses communication barriers, empowers non-verbal users, and provides a reliable platform for educational and therapeutic support.

Keywords: *assistive communication, impaired children, inclusive technology, mobile app, software quality, ISO 25010*

Introduction

Over the decades, assistive technology has steadily become a vital tool in enhancing the quality of life for individuals with physical, sensory, or cognitive limitations. It acts as a bridge connecting people's abilities with supportive tools that help them overcome daily challenges. From the simplest mechanical aids to complex digital systems, assistive technology remains grounded in the mission of improving accessibility and fostering greater independence. Over time, it has transformed the way people interact with their surroundings, empowering them to perform tasks that might otherwise be difficult or inaccessible.

The scope of assistive tools ranges widely—from low-tech devices such as adapted utensils to advanced digital solutions like speech-generating applications and screen readers. While their complexity differs, each plays a crucial role in helping individuals live more autonomous and inclusive lives. Every tool, whether basic or advanced, contributes to breaking down barriers that prevent full participation in everyday activities (UNDP, 2023).

With the rapid evolution of digital technology, assistive solutions are entering a new era. Emerging innovations in artificial intelligence, machine learning, and mobile computing are increasingly being integrated into assistive devices, making them adaptive, responsive, and personalized. These smart systems can now process gestures, facial expressions, and voice inputs to provide real-time feedback tailored to the user. Studies indicate that machine learning enhances the accuracy and responsiveness of assistive tools by dynamically adjusting to user behavior (Sensors, 2022). Similarly, the widespread availability of smartphones and tablets has enabled mobile-based assistive applications to extend support anytime and anywhere (Journal of Medical Systems, 2020). These advances go beyond convenience; they signal a shift toward inclusive and equitable access, where technology empowers people of all abilities to participate fully in society.

For children with impairments, however, communication remains a critical challenge. According to Griffiths, Clarke, and Price (2022), children with little or no functional speech often rely on alternative methods of expression such as vocalizations, facial expressions, or manual gestures. These communication difficulties are particularly common in conditions like intellectual disability, developmental delay, and neurodevelopmental disorders, which limit their ability to effectively express needs and thoughts. While many of these children comprehend language, their difficulties in producing speech result in a disconnect between cognitive awareness and communicative ability (Cadabams CDC, 2023). This communication gap can lead to frustration, emotional distress, and social isolation, as children are often unable to participate in meaningful interactions with peers, family, or educators (Sherred, 2020). In classrooms, such barriers reduce engagement and exacerbate developmental delays. Without appropriate support, these children risk being misunderstood or excluded, which can impact both their academic growth and emotional well-being.

Research emphasizes that investigating the communication challenges faced by impaired children is essential, given the profound impact on cognitive and social development (Zdravkova et al., 2022). Despite interventions, many children continue to face barriers to expressing thoughts and emotions, resulting in social withdrawal, frustration, and delays in learning (PubMed, 2020; PubMed, 2022). Current tools often fall short in adapting to diverse communication styles, highlighting the urgent need for more inclusive, responsive, and adaptive assistive systems (Zdravkova et al., 2022). Furthermore, global initiatives advocate for inclusive education and equitable access, underscoring the importance of technologies that leverage artificial intelligence to create personalized and effective support (WHO, 2021).

While technologies ranging from picture boards to speech-generating devices have advanced communication for impaired children, existing solutions still struggle to meet their dynamic needs, particularly those who depend heavily on body movements and non-verbal cues. Recognizing this gap, this study proposes a **mobile-based multimodal assistive communication application** that integrates gesture recognition, facial expression interpretation, text-to-speech output, and video-based learning using TensorFlow Lite machine learning models. By combining multiple input methods into a single interface, the system aims to provide flexible, adaptive, and natural communication pathways for impaired children, supporting both learning and everyday interaction.

Yet, despite progress, multimodal assistive communication technologies face significant limitations. Most existing systems are tested only in controlled settings with homogeneous groups, raising concerns about scalability and real-world applicability (Fager et al., 2022). Additionally, many tools fail to incorporate user, caregiver, and educator perspectives in their design, leading to poor alignment with children's needs and daily contexts (Karamolegkou et al., 2025). Current AAC applications often lack cultural sensitivity, context-aware accuracy, and seamless integration into educational or home routines. Importantly, studies tend to evaluate single modalities in isolation, rather than adopting a comprehensive multimodal framework.

This study seeks to bridge these gaps by developing, deploying, and assessing a mobile-based multimodal assistive system that integrates gesture, facial, and speech recognition. The system will be evaluated using the **ISO/IEC 25010:2023 framework**, which provides a structured standard for assessing software quality in terms of functionality, performance, usability, compatibility, reliability, and security (ISO, 2023). Aligning with this international standard ensures that the application is not only innovative but also reliable, user-friendly, and scalable across diverse educational and developmental settings.

Ultimately, this research contributes to inclusive educational technology by presenting a quality-driven, user-centered solution that empowers impaired children to communicate, learn, and participate more fully in daily life (Robinos et al. 2025). It underscores the broader importance of designing adaptive and accessible assistive technologies that respond to children's nuanced communication profiles, advancing both academic development and social inclusion.

The study aims to design, develop, and evaluate a mobile-based multimodal assistive communication application using TensorFlow Lite, specifically tailored for impaired children. The objectives are as follows:

1. **Design a user-centric and easily navigable multimodal assistive communication application** that integrates gesture recognition, facial expression analysis, and speech-to-text/text-to-speech technologies to support the diverse communication needs of impaired children.
2. **Develop the proposed system using TensorFlow Lite** to optimize performance on mobile devices, ensuring real-time interaction, adaptability, and accessibility in both home and educational settings.
3. **Evaluate the system's quality and effectiveness** based on the ISO/IEC 25010:2023 software quality framework, focusing on functional suitability, performance efficiency, usability, compatibility, reliability, and portability, while determining its influence on the communication ability, learning, and engagement of impaired children.

Methodology

Research Design

This study used a mixed-method design that combines both quantitative and qualitative approaches. This method was chosen to better understand how the system works and how users experience it. Using both strategies allows the researcher to collect measurable data while also capturing user perspectives. Quantitative methods, such as surveys and experiments, provided numbers and trends to test the system's usability and impact. Meanwhile, qualitative methods, like interviews and observations, revealed user experiences, emotions, and challenges. Together, these approaches offered a fuller picture of how children with communication difficulties use the system, ensuring findings were both reliable and user-centered.

Software Development Methodology

The system was developed using the Agile Scrum method, known for its flexibility and user-centered focus. Agile divides big projects into smaller parts, allowing faster delivery and easier adjustments when requirements change. Scrum works in short cycles called sprints (two to four weeks), where teams plan, build, test, and review system features. Unlike the traditional Waterfall model, which is rigid, Scrum allows teams to adapt quickly to user needs.

In this study, Scrum was essential since the system involved many technologies such as gesture recognition and text-to-speech. Each sprint focused on specific features, tested them, and refined them based on feedback. The Scrum team roles—Product Owner, Scrum Master, and developers—worked together to ensure clear goals, accountability, and continuous improvement. Daily meetings, sprint reviews, and retrospectives kept development on track and responsive. This approach helped avoid delays, ensured quality, and improved collaboration.

A. **Product Backlog –** The product backlog is a prioritized list of system features and tasks, including both main functions (like sign language recognition) and secondary ones (like interface improvements). The Product Owner managed this list and regularly updated it based on needs and feedback. In this study, the backlog helped organize development and focus on features most important for helping children communicate.

B. **Sprint Planning-**At the start of each sprint, the team selected key features from the backlog to focus on. These became the sprint backlog, with clear goals and tasks. In this study, sprint planning identified practical modules like gesture recognition that could be completed within the sprint timeframe. This made development more predictable and productive.

C. **Sprint Backlog-**The sprint backlog is the short-term task list chosen from the product backlog. It contains only the items the team commits to finish within a sprint. In this study, it included tasks like testing emotion detection or polishing the interface. The backlog kept the team focused and allowed daily progress tracking.

D. **Sprint-**A sprint is a 2–4 week cycle where the team works on specific tasks to produce a working part of the system. In this study, each sprint produced features like sign language recognition or facial emotion detection. Working in short cycles made development manageable and allowed quick improvements based on feedback.

E. **Daily Scrum-**The Daily Scrum is a 15-minute meeting where the team reviews what was done, what will be done, and any issues. In this study, the meetings (held online) helped monitor progress, share updates, and quickly address problems.

F. **Increment-**An increment is the result of a sprint—new features or improvements that are fully tested and integrated. In this study, increments included modules like text-to-speech or emotion recognition. Each increment was usable, provided checkpoints for feedback, and ensured the system stayed functional.

G. **Sprint Review-**At the end of each sprint, the team presented completed work to stakeholders for feedback. In this study, features like gesture recognition were tested and reviewed to ensure they met requirements and supported project goals.

H. **Sprint Retrospective-**After the Sprint Review, the team reflected on their process—what went well, what didn't, and how to improve. In this study, retrospectives helped identify issues like unclear task assignments and find solutions for better collaboration.

Sources of Data

The researcher used a multimodal assistive app as the main tool for data collection. This app included features like facial emotion recognition and sign language detection to support children with speech difficulties.

- **Primary Source**: Children with limited or no speech who used the app through gestures, facial expressions, and screen inputs. Their feedback was collected through online surveys.
- **Secondary Source**: Parents, caregivers, and special education teachers who provided insights about the children's needs and the app's usability.

Research Instrument

The study used three main tools:

1. **Online Literature Review** – to gather information on similar systems and best practices.
2. **Digital Surveys** – to collect structured feedback from children and their support groups.
3. **Structured Questionnaires** – to measure system performance using ISO 25010:2023 standards like usability and security.

Data Gathering Procedure

Data were collected using online surveys (via Google Forms) designed to match the system's features like gesture input and buttons. Responses were recorded digitally and analyzed using a Likert scale from "Very Unsatisfactory" to "Very Satisfactory." Literature reviews from online sources also supported the analysis. This process helped track usability trends, identify issues, and evaluate system performance.

Tools for Data Analysis

The researcher used diagrams to analyze and design the system:

- **Use Case Diagrams** – to show how users (children, caregivers, teachers) interact with system functions.
- **Data Flow Diagrams (DFD)** – to illustrate how data moves through the system, from input (like gestures) to output (like speech).

These diagrams helped define requirements, improve design, and guide testing.

Statistical Treatment of Data

Descriptive statistics were used to analyze survey responses. This helped measure the system's effectiveness and identify user feedback patterns that could guide improvements.

Ethical Considerations

The study followed strict ethical guidelines. Personal data, especially from children, was kept private and secure. The system was designed to be inclusive and avoid stereotypes. It was framed as a support tool—not a replacement for natural communication—so that children continued developing real social and interpersonal skills.

Results and Discussions

Objective 1: Design a user-centric and easily navigable multimodal assistive communication application that integrates gesture recognition, facial expression analysis, and speech-to-text/text-to-speech technologies to support the diverse communication needs of impaired children.

The design of the multimodal assistive communication application was guided by a user-centered approach, ensuring that the system responds directly to the real-world needs of impaired children. Data collection through online surveys and focus group discussions (FGDs) provided critical insights into required features, particularly the need for customizable communication buttons, gesture recognition, and facial emotion detection. These methods allowed the voices of both primary users (children) and support stakeholders (parents, caregivers, educators) to shape the system's features, ensuring inclusivity and practical relevance. This aligns with Griffiths, Clarke, and Price (2022), who emphasize that impaired children rely on varied forms of expression—such as gestures, facial cues, and vocalizations—and require communication tools that adapt to these modalities.

The findings were consolidated into a comprehensive **Software Requirements Specification (SRS)** document, which detailed both functional (e.g., gesture capture, emotion detection, speech conversion) and non-functional requirements (e.g., usability, performance, security). This ensured that the development process was not only technically sound but also tailored to the specific communication needs of the target users (Zdravkova et al., 2022). Early system models such as **use case diagrams** and **data flow diagrams (DFDs)** further clarified the interaction between users and system components, making the design transparent and structured.

A **working prototype** was then developed to validate the design assumptions. This prototype allowed impaired children and their support users to engage with features like customizable buttons, hand gesture recognition, and facial expression analysis. Early evaluations highlighted the importance of intuitive navigation and real-time responsiveness. According to Sherred (2020), providing seamless and frustration-free interaction is essential, as communication barriers can otherwise cause emotional distress and social withdrawal. By iteratively refining the prototype, the application evolved into a more reliable, user-friendly tool that directly addresses these concerns.

The system was also designed with dual roles—**Impaired Children Users** and **Support Users**. This structure allowed children to access simplified communication modes while caregivers and professionals monitored progress, managed profiles, and ensured accurate personalization. Such collaborative functionality is consistent with inclusive education principles promoted by WHO (2021), which stress the need for tools that support not just children but also the ecosystem of people guiding their development.

At the technical level, the system integrates a **multimodal input-output process**:

- **Gesture recognition** enables communication through body movements, vital for children with limited speech.
- **Facial expression analysis** provides real-time emotional context, supporting more natural interactions.
- **Speech-to-text and text-to-speech conversion** allows two-way communication, bridging the gap between impaired children and their caregivers or peers.

Together, these features deliver an **intuitive, adaptable, and context-aware platform**, ensuring that communication is not only possible but also meaningful and responsive to children's diverse abilities. The implication of this design is significant: by creating an accessible multimodal system grounded in real-world feedback and global quality frameworks (ISO, 2023), impaired children can achieve more independence, participate actively in education, and reduce risks of social isolation.

Summary Table 1 – Alignment of Design Features with Objective 1

Design Feature	**Data/Process Used**	**Supported Need**	**Implication**	**Supporting Reference**
Customizable communication buttons	Online surveys, FGDs, SRS documentation	Need for simple, intuitive interaction	Enhances usability and allows personalization	Griffiths, Clarke & Price (2022)
Gesture recognition	Prototype testing, Use Case & DFD models	Children relying on manual cues	Expands communication beyond speech, enabling inclusivity	Zdravkova et al. (2022)
Facial expression analysis	Prototype feedback, iterative refinement	Reliance on non-verbal emotional cues	Provides emotional context, making interactions more natural	Sherred (2020)
Speech-to-text/ Text-to-speech	Core app functionality	Bridging verbal and non-verbal communication gaps	Facilitates two-way communication and supports independence	WHO (2021)
Dual role system (Child & Support user)	Context diagram and SRS requirements	Need for collaboration with caregivers	Ensures monitoring, progress tracking, and personalization	WHO (2021); ISO (2023)
Real-time feedback & usability	Prototype evaluations	Immediate confirmation of communication attempts	Reduces frustration, increases engagement	ISO (2023)

Objective 2: Develop the proposed system using TensorFlow Lite to optimize performance on mobile devices, ensuring real-time interaction, adaptability, and accessibility in both home and educational settings.

To address this objective, the *Multimodal Machine Learning-Based Assistive Communication App for Impaired Children* was developed with the integration of **TensorFlow Lite**, which provides optimized performance of deep learning models directly on mobile devices. TensorFlow Lite ensures that gesture recognition, facial emotion detection, and other multimodal interactions can be processed **in real-time** without requiring constant internet connectivity or high computing power (TensorFlow, 2024). This significantly improves the system's usability for impaired children who rely on consistent, fast responses in both home and classroom environments.

The **Sign-in and Sign-up Interfaces** enhance accessibility and security by offering simple login methods, including Google authentication, which reduces the burden of remembering passwords for children and their caregivers. The **Homepage and Button Interfaces** enable adaptive communication through personalized buttons, categorized phrases, and customizable features such as icon selection and favorites. These interfaces, coupled with Tensor Flow Lite's lightweight architecture, support **smooth interaction even on lower-end devices**, making the app practical in underserved communities where access to high-spec gadgets is limited (Srinivasan & Kumar, 2023).

Crucially, the system's **Hand Gesture and Facial Emotion Recognition** demonstrates the potential of real-time multimodal learning. For example, the app detects a "Like" gesture with **99.36% accuracy** and identifies facial emotions such as "Happy" with **59.20% accuracy**, reflecting how mobile-optimized ML models can interpret visual and emotional cues effectively. This gives impaired children **alternative modes of expression**, reducing their dependency on text or voice alone and addressing barriers to communication often encountered in traditional assistive devices (Garg & Sharma, 2022).

The **Learn Sign Language Module** further illustrates adaptability by providing video-based tutorials for alphabets and numbers. This not only fosters literacy and numeracy but also integrates **interactive, engaging content** that enhances children's independence and confidence in communication. Moreover, the **Profile and Support App Interfaces**, which include QR code pairing, voice customization, and caregiver monitoring tools, ensure that families and educators are active partners in the communication process. Features like usage statistics (e.g., button press frequencies displayed through graphs) highlight the app's potential for **data-informed caregiving and teaching**, thereby creating feedback loops for continuous improvement in communication practices.

Overall, the use of TensorFlow Lite directly addresses Objective 2 by enabling **low-latency, mobile-friendly deployment** of multimodal ML features, ensuring the system is **accessible, adaptive, and effective across diverse settings**. This contributes to bridging gaps in inclusive education and home support, offering a scalable, affordable, and practical tool for impaired children and their caregivers.

***Summary Table 2 for Objective* 2**

Feature / Interface	Relevance to TensorFlow Lite Optimization	Implications for Accessibility & Adaptability
Sign-in / Sign-up	Lightweight login with secure authentication	Simplifies access for children and caregivers, reducing barriers.
Homepage & Button Interfaces	Efficient organization of personalized and predefined buttons	Ensures smooth, adaptive communication across contexts.
Gesture & Emotion Recognition	Real-time detection powered by TensorFlow Lite (99.36% for "Like")	Provides alternative, non-verbal communication channels for impaired children.
Learn Sign Language	Video-based tutorials for alphabets & numbers	Supports literacy, independence, and early communication development.
Profile & Support App	Voice settings, caregiver monitoring, QR pairing	Empowers families/educators through oversight, personalization, and usage analytics.

Feature / Interface	Relevance to TensorFlow Lite Optimization	Implications for Accessibility & Adaptability
Statistics & Data Visualization	Mobile-optimized graphs of button usage	Enables data-driven caregiving and teaching interventions.

Objective 3 – Evaluate the system's quality and effectiveness based on the ISO/IEC 25010:2023 software quality framework, focusing on functional suitability, performance efficiency, usability, compatibility, reliability, and portability, while determining its influence on the communication ability, learning, and engagement of impaired children.

The evaluation results demonstrate that the developed *Multimodal Machine Learning-Based Assistive Communication App* meets the **ISO/IEC 25010:2023 software quality standards**, affirming its effectiveness as a communication and learning support system for impaired children.

Functional Suitability

The system achieved an overall mean of **4.6**, with a perfect score of **5.0** for adaptability to user-specific preferences. This aligns with SOP 1.1 and Objective 1, which emphasize user-centric design and accessibility. The ability to tailor communication buttons and integrate multimodal inputs (button presses, hand gestures, and facial expressions) scored **4.8**, confirming its capacity to expand expressive range. High ratings for reliability over time (**4.6**) also suggest the system remains effective after repeated use. This implies that the app not only addresses the communication barriers of impaired children but also promotes inclusivity and personalization, essential qualities in adaptive assistive tools (ISO/IEC, 2023).

Performance Efficiency

The app recorded a mean of **4.49**, with its highest score (**4.87**) for operating under weak or inconsistent networks. This is vital in home or school settings where internet stability cannot be guaranteed (SOP 1.1, Objective 3). Reliability in error handling (**4.73**) and long-term stability (4.4) shows the system can withstand real-life caregiving sessions. Though real-time responsiveness was slightly lower (**4.13**), it still reflects adequate efficiency. These findings highlight that TensorFlow Lite's optimization ensures the app runs smoothly on resource-constrained devices, enabling sustained use without interruptions in daily communication.

Interaction Capability

With an overall score of **4.57**, the system's strongest feature was balancing performance with battery efficiency (**4.93**), crucial for mobile settings where devices must remain operational throughout the day. Multimodal responsiveness scored **4.67**, validating SOP 1.2 and Objective 1 on supporting real-time communication. Its consistent performance in caregiver tasks (4.53) shows practical integration in therapy and routine interactions. Although location-based features rated slightly lower (**4.20**), feedback still indicated contextual usefulness. This implies that the app is effective in bridging communication gaps, especially by offering accessible, multimodal, real-time support in diverse caregiving contexts.

Usability

The system scored highest in this category with a mean of **4.64**. User satisfaction (**4.93**) and first-time intuitiveness (**5.0**) confirm that the app is easy to learn and navigate, even for those with minimal technical expertise. This directly supports Objectives 2 and 3, ensuring minimal training time and seamless integration into existing routines. A manageable learning curve (**4.8**) and navigability (**4.33**) further highlight accessibility. While customization of communication buttons scored lower (**4.13**), this reflects an area for refinement. Implication-wise, usability ensures the app fosters **low cognitive load**, essential for children and caregivers in emotionally sensitive communication situations.

Compatibility

The app demonstrated strong device compatibility with an overall score of **4.4**. Reliability across Android devices scored **4.93**, ensuring smooth performance even on older or lower-end devices (SOP 1.2). A consistent user experience across devices (**4.87**) further validates its adaptability. While basic support for accessibility features scored **4.13**, and external platform integration scored **4.0**, these areas represent opportunities to expand future interoperability. Overall, compatibility findings confirm the system is accessible to a wide user base, reducing exclusion caused by hardware limitations.

Portability

Scoring **4.52** overall, the system's ability to maintain functionality across screen sizes and orientations achieved **4.93**, highlighting its adaptability across smartphones and tablets (SOP 1.3). Consistency across devices (**4.87**) reinforces portability, while multilingual support (4.0) reflects initial inclusivity with potential for growth. The strong score for on-the-go caregiving (**4.67**) affirms its practical use in mobile therapy and educational contexts. This suggests the app not only supports learning but also strengthens engagement by allowing children to communicate flexibly, regardless of setting.

Overall Implications

The findings affirm that the system is **reliable, efficient, and user-friendly**, directly addressing ISO/IEC 25010:2023 quality standards. High ratings in functional suitability and usability emphasize its role as an accessible, personalized, and adaptive tool. Performance efficiency and portability reinforce its practical application in variable environments, ensuring children are not left behind due to technical constraints. The implications are clear: the app enhances **communication ability, learning engagement, and social participation** for impaired children by combining machine learning optimization with a user-centric design.

Summary Table 3 – Evaluation Based on ISO/IEC 25010:2023

Dimension	Key Findings (Mean Scores)	Implications for Impaired Children
Functional Suitability	Adaptability (5.0), Multimodal Support (4.8), Reliability over time (4.6), Overall Mean = **4.6**	Enhances expressive range and inclusivity through personalization and multimodal features.
Performance Efficiency	Weak Network Support (4.87), Error Handling (4.73), Responsiveness (4.13), Overall Mean = **4.49**	Ensures stable communication even in resource-constrained environments.
Interaction Capability	Battery Balance (4.93), Multimodal Responsiveness (4.67), Caregiver Tasks (4.53), Overall Mean = **4.57**	Provides real-time, reliable support for daily communication and therapy.
Usability	User Satisfaction (4.93), First-time Intuitiveness (5.0), Learning Curve (4.8), Customization (4.13), Overall Mean = **4.64**	Reduces cognitive load and promotes stress-free interaction for children and caregivers.
Compatibility	Android Reliability (4.93), Consistency Across Devices (4.87), Integration (4.0), Overall Mean = **4.40**	Accessible across devices, ensuring broad usability for diverse users.
Portability	Screen Adaptability (4.93), Device Consistency (4.87), Multilingual Support (4.0), On-the-Go Use (4.67), Overall Mean = **4.52**	Strengthens independence and flexibility in home, school, and mobile environments.

Implementation marks a crucial phase in the system development lifecycle, where design models and concepts are transformed into a functional solution that addresses real-world communication barriers. As Chen and Liu (2020) note, this stage bridges theoretical innovation and practical application, ensuring that proposed features are realized in a context-sensitive manner. To support accessibility and adoption, a hybrid learning strategy was used, combining digital training with guided, home-based instruction. This approach allowed users and their caregivers to learn the system at their own pace, building familiarity with its customizable communication features.

Developed with a **user-centered design philosophy**, the system emphasizes inclusivity and ease of use. Its interface accommodates users with varying levels of digital literacy, enabling even first-time users to confidently navigate and maximize its assistive functions.

Core features—including machine learning–based hand gesture recognition, real-time facial emotion detection, customizable communication buttons, and an intuitive interface—enhance adaptability across diverse needs and caregiving contexts. Feedback from end-user surveys confirmed its responsiveness, accessibility, and ability to address complex communication challenges. Overall, findings affirm the system's alignment with **international quality standards** and highlight its potential to advance assistive communication technology. The solution presents a scalable, future-ready tool for empowering non-verbal individuals in both educational and therapeutic settings.

Conclusions and Recommendations

The comprehensive evaluation of the multimodal assistive system demonstrated **strong performance across all ISO/IEC 25010:2023 quality dimensions**, achieving an overall weighted mean of **4.57**. This result confirms the system's effectiveness as a customizable, inclusive, and intelligent communication tool tailored to the needs of impaired children. High ratings in **functional suitability, reliability, performance efficiency, usability, compatibility, and portability** underscore its robust design and practical applicability in real-world caregiving and educational contexts. Children with communication impairments often face barriers in expressing basic needs, participating in daily routines, and engaging socially. These challenges may result in caregiver stress, weakened family bonds, and limited learning opportunities. By addressing these communication gaps, the system provides an accessible and dependable platform that enhances **self-expression, autonomy, and emotional well-being**. Core features such as gesture recognition, facial emotion detection, and customizable speech outputs empower children to communicate more clearly, reducing isolation and strengthening relationships with caregivers, teachers, and peers.

The study highlights that the system not only supports **functional communication** but also contributes to **inclusive education and social participation**. Its adaptability makes it a valuable tool in diverse settings, ranging from home-based care to classrooms and therapy sessions. Importantly, the findings affirm that a **user-centered, technology-driven design** can mitigate barriers that hinder the social, emotional, and developmental growth of impaired children. However, some limitations remain, particularly in **multilingual support, integration with external assistive platforms, and long-term scalability**. Addressing these areas is crucial to expanding the system's inclusivity and cultural responsiveness.

To maximize the system's impact, several refinements are recommended. First, its **responsiveness and contextual accuracy** should be enhanced to better support dynamic caregiving and classroom interactions, ensuring smoother real-time communication. Expanding **multilingual and cultural support** is also necessary, particularly through local language packs and culturally relevant voice outputs, to make the tool more inclusive across diverse populations. In addition, efforts should be made to **improve interoperability** by integrating the system with third-party assistive technologies, APIs, and accessibility tools such as screen readers and adaptive switches, allowing for broader usability among children with varied needs. To support adoption, **structured training and orientation programs** for caregivers, therapists, and educators must be strengthened, reducing the learning curve and promoting sustained use. Moreover, conducting **longitudinal evaluations** in home, school, and therapy settings will help measure the system's long-term effects on communication, learning outcomes, social engagement, and caregiver stress reduction. Finally, the system should undergo **iterative development and continuous testing** guided by the ISO/IEC 25010:2023 software quality model, with greater emphasis on areas such as security and maintainability, to ensure scalability, sustainability, and readiness for wider deployment. By implementing these recommendations, the system has the potential to evolve into a **universally adaptive assistive platform**, enabling impaired children to communicate effectively, strengthening family and social integration, and supporting inclusive education aligned with global standards.

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