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Advancing Accessibility: Leveraging Technology to Empower Deaf and Hard of Hearing Students in STEM Higher Education

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Abstract

This systematized review examines the current technological interventions aimed at enhancing accessibility for Deaf and Hard of Hearing (DHH) students in STEM higher education. The study identifies key barriers, evaluates the effectiveness of existing solutions, and gaps in the literature. Among the findings, sixty percent of the reviewed articles focused on machine learning for sign language translation, yet most lacked real-world testing. Only eleven percent of the studies addressed classroom-specific accessibility challenges, and a significant geographic disparity was observed, with limited representation from low- and middle-income countries. This review highlights the need for more inclusive and user-centered designs, along with increased funding and attention to diverse educational contexts.

Keywords

Systematized Review, Deaf & Hard-of-Hearing, Undergraduate Education, Assistive Technology

Introduction

Diversity and inclusion are essential pillars of progress in Science, Technology, Engineering, and Mathematics (STEM) fields. However, Deaf and Hard of Hearing (DHH) students remain significantly underrepresented in higher education, particularly in STEM disciplines [1], [2]. Despite concerted efforts by organizations such as the National Science Foundation (NSF) and AccessComputing to promote inclusivity [3], DHH students continue to encounter unique

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barriers. These barriers include communication challenges, limited accessibility to STEM-specific vocabulary, and a lack of tailored educational tools that address their needs.

Current technological interventions, such as e-learning platforms and captioning tools, while beneficial, often fall short of addressing the unique challenges faced by DHH students in STEM. These technologies frequently lack the specificity required for complex STEM topics and may not fully support the development of essential skills such as mathematical proficiency and problem-solving. Furthermore, the diversity of sign languages and the limited availability of STEM-based vocabulary in these languages add to the complexity, making it difficult for DHH students to achieve their full potential in these fields [4], [5].

To address these challenges, this work takes a systematized approach to review the current state of technology and innovative approaches aimed at enhancing the academic success of DHH students in STEM higher education. Specifically, the aims of our review are as follows:

1. Identify key barriers faced by DHH students in STEM higher education.
2. Evaluate the efficacy of current technological solutions in enhancing the academic experiences of DHH students.
3. Reveal existing gaps in technology and educational strategies.
4. Propose evidence-based recommendations for developing and implementing more effective educational technologies.
5. Inform and influence policies aimed at improving accessibility, entry into STEM fields, and retention rates for DHH students.

Our review reveals several key findings: a significant gap in user studies that involve real-world testing with DHH students, limited funding in accessibility literature, and a notable lack of focus on classroom-specific accessibility solutions. Additionally, there is a disparity in geographic distribution, with most publications originating from technologically advanced regions, leaving low- and middle-income countries underrepresented.

The contributions of this work include identifying the critical gaps in current accessibility research for DHH students in STEM, highlighting the need for more inclusive and user-centered design practices, and suggesting future research directions that prioritize real-world testing and classroom integration of accessibility technologies. This review aims to guide researchers and practitioners in developing more effective and equitable solutions that can truly empower DHH students in STEM higher education.

Background

In recent years, the global push for diversity, equity, and inclusion has significantly impacted higher education, with institutions increasingly focusing on creating accessible environments for all students, including those with disabilities [6], [7]. Research indicates that despite these efforts, DHH students remain underrepresented in STEM fields. This under-representation stems from several factors, including social biases, communication barriers, and the lack of adequate educational resources. For example, DHH students often face inaccessibility to incidental learning opportunities, which are crucial for grasping scientific concepts and participating in professional networks [8]. Also, DHH students (along with other students with disabilities) might also be placed into "special education" classrooms in secondary school due to a lack of teacher training and resources to integrate students into classrooms, which can significantly hamper preparations for the academic demands of university STEM programs [9]. This under-representation is not merely a reflection of broader societal challenges but also highlights specific barriers that DHH students face in STEM higher education, such as the limited availability of accessible learning materials and real-time communication tools [10].

The World Health Organization estimates that over 5% of the world's population—approximately 430 million people—experience hearing impairment, with this number expected to rise to over 700 million by 2050 [11]. Within this population, DHH students encounter unique challenges in educational settings, particularly in STEM disciplines where communication and access to specialized vocabulary are critical for success. Without accommodations, learning loss throughout the educational pathway occurs with some publications reporting DHH students performing as seniors in high school at fifth- and sixth-grade levels in computation and problem solving [9]. In addition, the lack of accommodations such as real-time captioning and sign language interpreters during interactive STEM sessions makes it difficult for DHH students to participate fully [8]. Other challenges present from faculty needing time and education to support students in their courses including coordinating room reservations, adaptions to course material (accessible videos), and knowledge of the processes at their institution [12].

Despite global efforts to enhance accessibility, the technological solutions available to support DHH students in STEM education are often limited in scope and effectiveness [13]. There have been technological implementations to support DHH students for decades now, from specific software applications for word problem comprehension to full automatic translation of sign language [9], [14]. Current technology implementations typically revolve around captioning, however this can be problematic as students need to split their focus between a speaker, captions, visual materials and more [15]. Another example is providing tablets and captioned, ASL-signed content to support lab course, although the specialized vocabulary inherent in labs requires a high level of consistency when developing signed content [16]. Additionally, it is recommended to account for various modes of communication among the DHH population as there are different options for signing, speechreading, and level of hearing [14], [17]. Another option for technology includes 3D images and avatars, which can accommodate different speeds of signing and provide different angles, unlike standard videos [14]. However, these technologies are often inaccessible in lower-income regions, where the infrastructure to support such innovations may be lacking [18], [19].

Finally, the rapid pace of technological advancement has not always translated into practical applications that meet the diverse needs of DHH students in STEM contexts [20]. This discrepancy highlights the need for more inclusive and context-specific technological interventions that can be effectively implemented across different educational environments. The barriers to implementation all pose challenges for any technological developments to support DHH students in STEM education, however have the potential to not only promote retention and success of DHH students, but all students (i.e., Universal Design for Learning, UDL) [9], [21].

Methods

The systematized review is an "attempt to include one or more elements of the systematic review process while stopping short of claiming that the resultant output is a systematic review" [22].

The search strategy for this review was developed for a separate scoping review aimed at understanding factors that contribute or are barriers to the success in STEM and computing-related undergraduate programs among students who are deaf or hard of hearing. In the present review, a subset of these articles was selected based on the presence of the following key terms in the title or abstract: "smart phone", "mobile device", "cell phone", or "artificial intelligence". This resulted in 438 records, 194 of which were duplicates. A single reviewer screened all 244 records for relevance based on title and abstract, excluding 175 records unrelated to the present topic. Full text was available for the remaining 69 records. A second reviewer screened these 69 records included records to confirm relevance; 22 records were excluded at this stage. Through this process, 47 records were identified as relevant to the present topic. See Figure 1 for the complete PRISMA flow diagram [23].

The following data items were extracted from all relevant articles: country in which study was conducted; country (or countries) of author(s); aim of paper (or study); funding source(s); relevance to STEM educational setting; whether the technology was tested with the population of interest; study method; start & end date of data collection; inclusion & exclusion criteria for sample population; total number of participants; technology type; how was the technology was used; outcome(s) measured; result of the intervention(s).

Results

This systematized literature review examined various technological interventions aimed at improving accessibility for individuals with hearing impairments. The review reveals several important trends and gaps in the current body of literature.

User Studies and Real-World Application

One of the most striking observations is the limited availability of user studies involving the target population. For instance, Fernanández et al. [24] and Park et al. [25] proposed innovative solutions like educational games and real-time sign language translation systems, yet lacked comprehensive testing with the intended users. This gap raises concerns about the usability and long-term impact of these technologies, as many of the solutions remained in prototype stages without being deployed in real-world environments. Hou et al [26] and Berger and Maly [27] also exemplify this trend, focusing on technical development rather than practical application. However, none of the tested studies are real-world applications.

Focus on Machine Learning for Sign Language Translation

Another prominent trend is the reliance on machine learning techniques to translate sign language into text or voice and vice versa. Approximately 60% of the literature fell into this category, (including the works of [28]–[55]) which highlight the potential of machine learning to bridge communication gaps for individuals who are deaf or hard of hearing. These articles typically

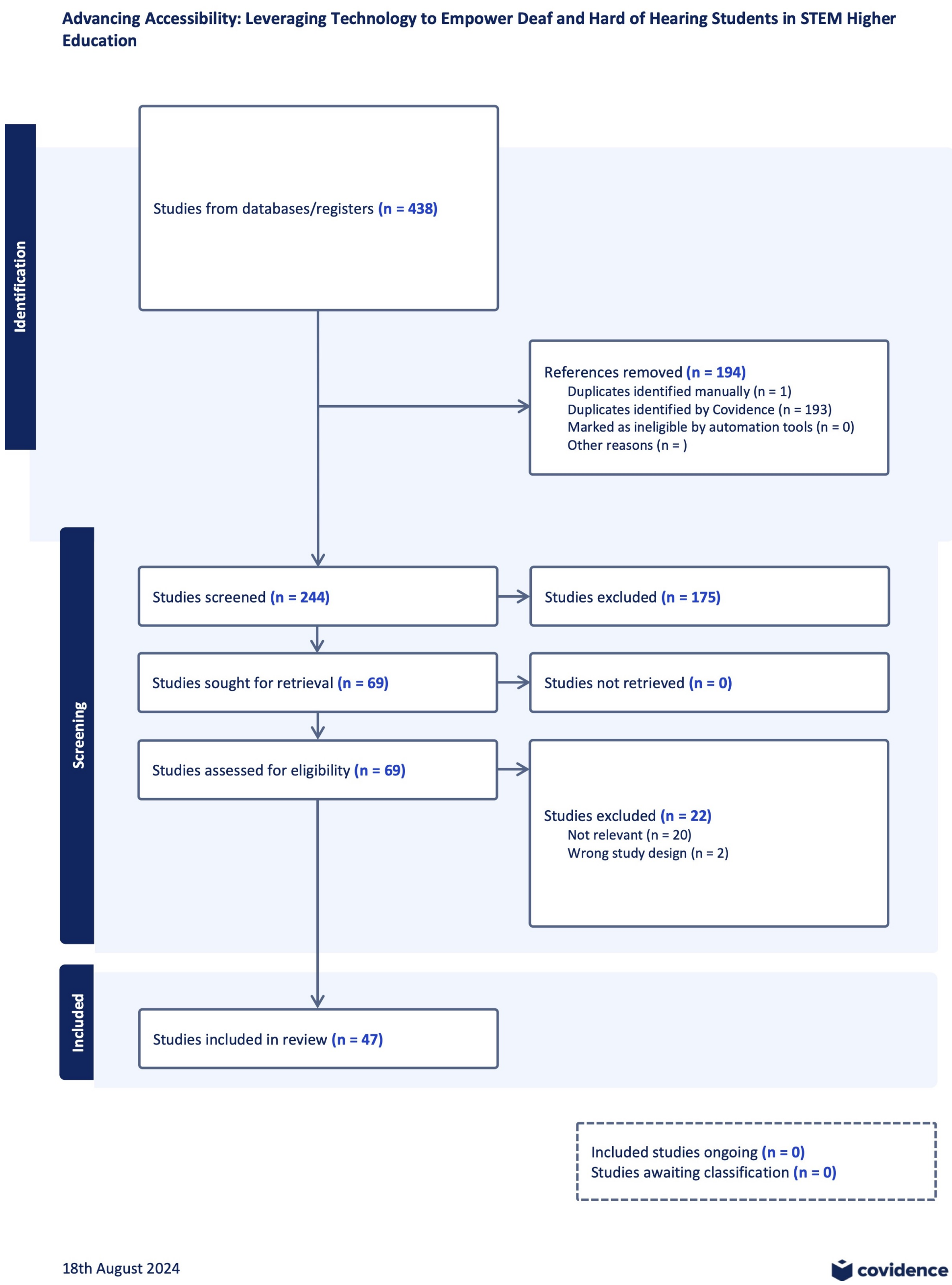

Figure 1: PRISMA flow diagram [23].

report high levels of precision in controlled environments, focusing on improving model accuracy. However, the emphasis on machine learning also reflects a broader gap in addressing other accessibility challenges, particularly in contexts where communication is not the only barrier. Large Language Models (LLMs) such as ChatGPT and chat bots are other technology that could be explored to enhance communication accessibility for the hearing impaired [56], however the lack of tested application of LLMs to address accessibility for the hearing impaired may be, at least in part, explained by how recently LLMs became available to the public.

Limited Focus on Classroom Accessibility

Despite the wide range of technology explored, there is a noticeable dearth of studies aimed specifically at enhancing accessibility in educational settings. Only a small fraction of the literature (approximately 11%) directly addresses accessibility challenges in classrooms, particularly for students with hearing disabilities [24], [57]–[60]. This gap is concerning, given the critical role of education in enabling individuals with disabilities to achieve independence and participate fully in society. The limited focus on classroom solutions underscores the need for more research that integrates accessibility technologies into educational infrastructures.

Funding for Accessibility Literature

Another significant observation is the lack of acknowledged funding across the corpus. Among the articles included in this study, only 11% mentioned receiving funding. The funded organizations mentioned include the Project of Students Grant Agency, FIM, University of Hradec Kralove, Czech Republic [27], JST CREST Grant [61], the Erasmus+ Program of the European Union through the Project EduTech under Grant [48], [62], Barrier-free communication system for hearing-impaired people based on Chinese lip translation [43],and FAPERGS ARD [54]. This highlights a potential barrier to conducting robust accessibility research, as increased financial support is necessary to enable more comprehensive studies, including long-term evaluations and real-world applications. Greater funding opportunities are crucial to advancing the field of accessibility research and ensuring that solutions are effectively implemented and sustained.

Geographic Distribution

The articles reviewed were conducted across a range of countries, reflecting a global interest in accessibility solutions. However, there is a noticeable concentration of publications in technologically advanced regions, with limited representation from low- and middle-income countries. From the 47 selected eligible accessibility records, only three were written by authors in South America [24], [54], [62] representing 6.4%, while only four were from authors in Africa [35], [59], [63], [64] representing 8.5%. This geographic disparity suggests that the benefits of these innovations may not be reaching some of the populations that could benefit the most.

International Developments

The bar chart (Figure 2) highlights the distribution of accessibility articles across different countries, with India leading with 11 publications, followed by the USA and China, each with 4 articles. Bangladesh and the UAE also contribute significantly, with 3 articles each. The rest of the countries have contributed one or two articles. This distribution only account for articles we found eligible for this review.

India has the highest number of publications, focusing on various technological solutions for accessibility, including wearable technology like smart gloves, computer vision systems for sign language recognition, and AI-based real-time translation systems. These technologies aim to bridge communication gaps for individuals with hearing and speech impairments, particularly in educational and social settings.

The USA also contributes to accessibility literature, with a focus on integrating AI and machine

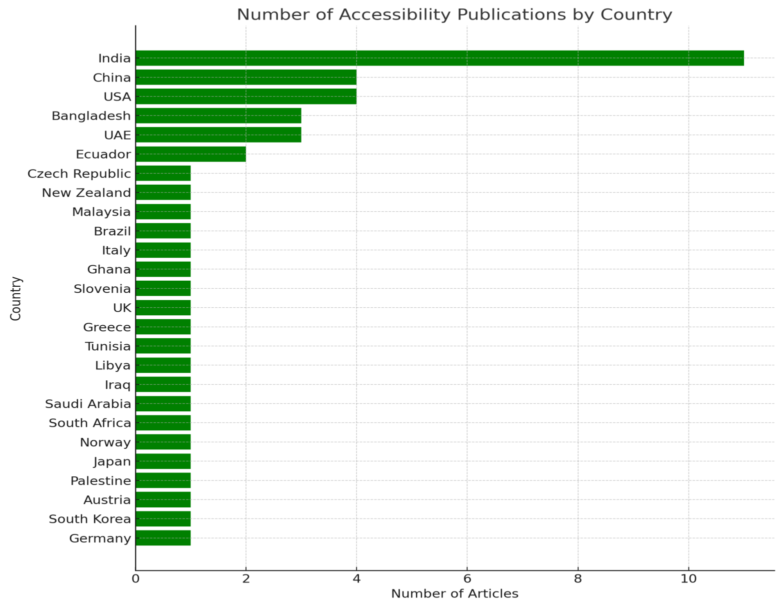

Figure 2: Accessibility technology publications by country.

learning for gesture recognition, virtual reality applications for sign language learning, and mobile-based solutions. These articles often aim to make educational settings more inclusive and provide tools for improving communication between hearing and non-hearing individuals.

China's efforts toward accessibility include developing real-time translation systems using smartphones and deep learning models, with a focus on improving accuracy and efficiency in recognizing and translating sign language. The technology solutions often emphasize privacy and efficiency, making them suitable for broader applications, including mobile and wearable devices.

It is worth noting that some of the of the literature represent collaborative efforts between different countries, although the bar chart only reflects the first author's country. For example, certain publications involve collaboration between China and the USA, as well as between European and Asian countries [24], [26], [33], [48], [58], [62]. These collaborative efforts highlight the global nature of accessibility publications and the shared goal of developing inclusive technologies that transcend geographical boundaries.

Accessibility Solutions

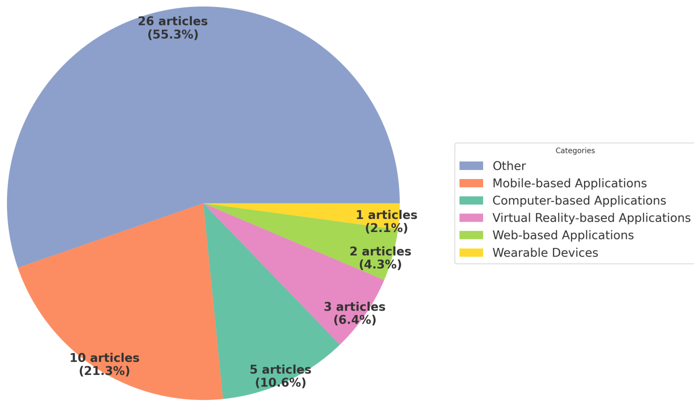

Figure 3: Types of accessibility technology solutions.

The pie chart (Figure 3) represents the distribution of accessibility solutions across various technology categories based on the dataset. Mobile-based applications dominate the landscape [24], [25], [28], [37], [38], [44], [54], [65], reflecting the widespread use of smartphones and tablets as key tools for improving accessibility. This prevalence is likely due to the portability and increasing capabilities of mobile devices, making them ideal for delivering accessible content and services on the go. However, mobile accessibility is more suited for a social setting than an educational setting. Some applications are mobile, and desktop combined [63], while others are web and mobile [27], [34].

Web-based applications also feature prominently, highlighting the importance of the internet in providing accessible solutions. With more services moving online, web-based platforms have become essential for ensuring accessibility in digital spaces, particularly for those with disabilities [51], [58], [62].

Wearable devices, such as smartwatches and smart gloves, have emerged as another significant category [26], [33], [40], [57], [66], [67], showcasing the integration of technology into everyday items to enhance accessibility. These devices often provide real-time assistance and monitoring, offering practical solutions for individuals with various impairments.

Virtual Reality (VR)-based applications [41], [48], [68], [69], while less common, are noteworthy for their innovative approach to accessibility. VR technology has the potential to create immersive experiences that can be tailored to meet the needs of users with disabilities, offering new ways to interact with digital environments.

Computer-based applications continue to play a role, particularly in more traditional settings where desktop or laptop computers are the primary tools for accessibility solutions [32], [61]. These applications are often used in professional and educational contexts, where more robust processing power may be required.

The "Other" category encompasses various technologies that, while not fitting neatly into the primary categories, still contribute significantly to advancing accessibility. For instance, Mahbub et al. [31] developed a solution for automating the identification of Bangla Sign Digits by comparing the effectiveness of handcrafted and deep neural network features. However, the study did not specify the medium through which the final solution would be presented to users. Similarly, Yin et al. [39] introduced a neural network-based sign language translation model that combines 2D/3D Convolutional Neural Networks (CNNs) with Transformer Decoders for translating sign language from video input. However, they did not indicate how the final solution would be deployed or used by end users. Similar articles in this category include [29], [30], [35], [36], [42], [43], [45]–[47], [49], [50], [52], [53], [55], [59], [60], [64], [70]. This category includes the diversity of approaches being taken to address accessibility challenges across different contexts and user needs using machine learning and AI.

Discussion

The findings of this systematized review uncovered several key trends and gaps in the current landscape of technological interventions aimed at enhancing accessibility for DHH students in STEM higher education. These results have important implications for the field and suggest both promising directions and critical areas in need of further attention.

The review highlights several persistent barriers that DHH students face in STEM higher education. Communication remains a primary barrier, as DHH students often struggle with accessing complex STEM-specific vocabulary and content, which are frequently not well-represented in sign languages.

One of the most significant findings is the limited availability of user studies involving real-world testing with DHH students. For example, Hou et al [26] achieved high accuracy in controlled environments but remains untested in real classrooms. This gap highlights a broader issue in accessibility literature: the emphasis on technical development over practical application. While many of the reviewed records proposed innovative solutions, such as educational games and sign language translation systems (Figure 3), these technologies often remained at the prototype stage without comprehensive testing in real-world environments. This raises concerns about the long-term usability and impact of these technologies. The lack of real-world validation highlights the need for future research to prioritize user-centered design and practical deployment to ensure that these interventions can truly benefit DHH students in STEM contexts.

Another interesting finding is the heavy reliance on machine learning for sign language translation, which dominated a significant portion of the corpus. While this focus on machine learning reflects the field's technological advancements, it also reveals a potential overemphasis on communication accessibility at the expense of other critical challenges faced by DHH students in STEM. Although, this theme may be influenced by the terms (e.g., ”cell phone”) used to select records for this sub-analysis, as cell phones, etc. are primarily used for communication. Regardless, many publications failed to address the complexity of STEM-specific vocabulary and the unique cognitive demands of STEM education. This suggests a need for a more holistic approach to accessibility, one that goes beyond communication and considers the broader educational challenges DHH students face.

For instance, while several articles provides a functional tool for communication, their solutions were limited to translating basic ASL alphabet and words [29], [30], [35], [39], [41], [42], [45],

[46], [50], [51], [66], thereby limiting their impact. This narrow focus limits the efficacy of these solutions in enhancing the overall academic experience for DHH students.

An unexpected and somewhat disappointing finding was the limited geographic diversity of the literature reviewed (Figure 2). The majority of the publications originated from technologically advanced regions notably India, China, and the USA, with minimal representation from low-income and middle-income countries. This geographic disparity raises questions about the global applicability of the findings and suggests that the benefits of these technological innovations may not be reaching some of the populations that could benefit the most. Future research should strive to include more diverse geographic contexts to ensure that accessibility solutions are equitable and globally relevant.

Further, considering the significant influence practitioners and educators have in driving accessibility research [71], this study serves as a call to action for more proactive, collaborative engagement across multiple domains in computer science [72]. For educators, integrating accessibility research into various fields—including cybersecurity, software engineering, systems design, blockchain, and AI—promotes an academic culture where inclusivity is not an afterthought but a foundational element of the curriculum. This movement is gaining traction, especially within human-computer interaction (HCI) research [73]. By embedding accessibility into both curriculum and research [74], [75], educators encourage students to recognize and address the diverse needs of society, a core goal of HCI [76]. This approach fosters a generation of technologists who are not only skilled but also empathetic advocates for inclusive innovation [77], [78].

Practitioners, on the other hand, are at the forefront of designing and implementing technological systems. They have a unique opportunity to apply insights from accessibility research directly to real-world applications [79]. By translating this extensive body of research into actionable solutions [80], including policy findings turned into practical applications [81], practitioners can significantly enhance the experiences of users who rely on accessible technologies—particularly those pursuing careers in STEM fields [9]. For instance, accessibility improvements in collaboration software or data visualization tools facilitate more equitable participation for DHH individuals in both educational and professional STEM environments [2], [82]. This approach not only supports DHH users but also enhances the overall user experience through the principles of Universal Design, which benefit all users [83], [84].

Gaps in the Literature and Future Directions

Several gaps in the literature warrant attention. First, the lack of long-term studies assessing the sustained impact of these technologies is a significant gap. For example, some studies [24], [25] show initial promise of using technology but do not extend beyond short-term evaluations. Additionally, there is a need for more inclusive design practices that involve the target population from the outset. The tendency of many studies (e.g., [26], [27]), to prioritize technological innovation over user needs, leads to solutions that may not be fully aligned with the experiences and preferences of the intended users.

Future research should prioritize real-world testing and user-centered design approaches. Expanding the focus to include more comprehensive educational accessibility solutions could have a transformative impact on the inclusion of students with disabilities in mainstream educational settings. Researchers should also consider conducting studies in diverse geographic and socioeconomic contexts to ensure that the benefits of accessibility technologies are equitably distributed.

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