Critical Analysis of Technological Advancements in STEM Education Accessibility

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As immersive technologies reshape STEM education, accessibility for blind and visually impaired(BVI) learners remains critically overlooked. This paper evaluates emerging AR, VR, and AI-based educational tools through a comparative case study analysis of four technical artifacts. The artifacts are assessed through a revised accessibility evaluation framework based on WCAG 2.2 in terms of non-visual interaction, multimodal feedback, and compatibility with assistive technologies. Our findings reveal that while pedagogical innovation is accelerating, inclusive design has not kept pace as most tools lack basic accessibility features. We propose revised guidelines for immersive educational contexts and argue for accessibility to considered in early stages of design and development in future STEM technology development.

CCS Concepts: • **Human-centered computing → Heuristic evaluations**; **Accessibility design and evaluation methods**; *Accessibility systems and tools*; • **Social and professional topics → People with disabilities**; • **Applied computing → Interactive learning environments**.

Additional Key Words and Phrases: accessibility, blindness, augmented and virtual reality; inclusive education, STEM education

1 Introduction

As technological advancement is rapidly developing, educational tools are undergoing major shifts from static, text and image-based experiences to interactive and immersive experiences. Technologies like augmented reality (AR), virtual reality (VR), and artificial intelligence (AI)-based systems show potential for opening new opportunities for more engaging and personalized learning environments and experience. However, this new innovative trend also produces risks for reinforcing the digital divide, especially for blind and visually impaired (BVI) individuals. Despite the growing emphasis on inclusive education, many educational technologies either marginally address accessibility needs or do not fully consider them. Furthermore, while existing frameworks like Web Content Accessibility Guidelines (WCAG) [W3C 2024] offer important guidelines for evaluating accessibility for web-based platforms, their applicability for dynamic, immersive technologies remains underexplored. This raises critical questions about their sufficiency for emerging tools, especially in STEM learning environments.

Existing research reflects the increasing awareness of the potential and challenges of accessibility in education, yet important gaps still remain. Prior works have existed in evaluating research and technological tools in educational contexts ([Avila-Garzon et al. 2021], [Al-Ansi et al. 2023], [Creed et al. 2024], [Hamash et al. 2024], [Quintero et al. 2019], [Hamash et al. 2024]) or creating educational tools to enhance motivation or interaction in education environments ([Dünser et al. 2012], [Gunturu et al. 2024], [Monteiro et al. 2023]). There have also been research on creating assistive technology for specific uses in everyday life ([Li et al. 2023], [Kane et al. 2008], [Lazar et al. 2019], [Sultania et al. 2023], [Wu et al. 2017], [Zong et al. 2022]). However, much of the existing research has tended to specialize in one area, and many studies have failed to fully consider accessible technical advancements as a fundamental requirement for inclusive educational environments.

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This study seeks to address these gaps and bring various areas together. Critical comparative analysis of emerging STEM education technologies and their accessibility for BVI users will be analyzed. Through this process, the following research questions will be answered:

- How well do state-of-the-art educational technologies integrate accessibility considerations for BVI users?
- How does integrating immersive technologies and AI impact the accessibility of STEM learning experiences for BVI students?
- How do current accessibility guidelines align with the needs of immersive and AI-powered STEM educational tools, and what key attributes should be considered in future accessibility standards?

And through the process of answering these research questions, the study seeks to make three main contributions:

- We provide context-specific insights on how emerging educational tools reflect or ignore non-visual interaction needs, based on technical evaluation and experiential analysis.
- We offer a framework-level critique of how current accessibility standards, particularly WCAG, fail to address the needs of BVI users in immersive environments.
- We propose a prototype extension of WCAG, introducing new accessibility attributes tailored to VR/AR and AI-integrated educational systems, and demonstrating a design model for more inclusive future standards.

By systematically connecting technical analysis, user-centered considerations and accessibility guideline evaluations, this work aims to push the fields of education technology, accessibility research, and human-computer interaction (HCI) toward a more equitable digital environment for BVI learners.

2 Related Work

This study builds upon literature in accessibility, inclusive education, social inclusion, HCI, learning sciences, human-centered design, and VR/AR. Prior studies can be grouped into three key areas: (1) trends, opportunities, and challenges in accessibility integration; (2) assistive and adaptive technologies bridging the digital divide; and (3) education technology related advancements not explicitly designs for accessibility.

2.1 Broader Trends, Opportunities, and Challenges in Accessibility Integration

Recent studies highlight the potential of emerging technologies to enhance accessibility in education, particularly XR (VR/AR). Avila-Garzon et al. [Avila-Garzon et al. 2021] conducted a 25-year bibliometric analysis of AR in education, though it omitted the rapid post-COVID developments including ChatGPT. Similarly, Al-Ansi et al. [Al-Ansi et al. 2023] analyzed 1,536 VR/AR-related education articles from 2011–2022, observing post-pandemic growth but overlooking accessibility considerations for learners with disabilities, a critical aspect of inclusive education. In contrast, Creed et al. [Creed et al. 2024] directly addressed accessibility barriers in VR/AR via two multidisciplinary sandpits involving interdisciplinary experts to highlight inclusive design across software, hardware, ethics, and collaboration. Complementary findings from Hamash et al. [Hamash et al. 2024] identified XR's potential in blending tactile, audio, and low-cost tools to improve accessibility while Quintero et al. [Quintero et al. 2019] found that fewer than 10% addressed visual impairment, underscoring the field's limited progress in inclusive educational design.

2.2 Assistive and Adaptive Technologies to Bridge the Digital Divide

The second group focuses on assistive and adaptive technologies developed for equitable digital access. Examples include *TangibleCircuits* [Davis et al. 2020] for tactile engineering learning, *Toucha11y* [Li et al. 2023] for accessible touchscreen kiosks via smartphones using a roboticic tool, and earlier redesigns for touchscreens like *SlideRule* [Kane et al. 2008], and Lazar's guidelines [Lazar et al. 2019]. Additionally, Sultania et al. [Sultania et al. 2023] developed wearable haptic feedback systems for visual impaired students while Wu et al. [Wu et al. 2017] and Zong et al. [Zong et al. 2022] worked to enhance accessibility for 2D images or data visualizations.

2.3 Technological Advancements Aligned with Educational Objectives

This category includes educational technologies that are not explicitly designed for accessibility. Dünser et al. [Dünser et al. 2012] introduced *Augmented Books*, an AR framework for interactive AR books though excluding consideration for disability accessibility. Recent studies like *Augmented Physics* [Gunturu et al. 2024] use AR and machine learning to transform textbook diagrams into interactive simulations that show potential for immersive learning yet unintentionally reinforces the digital divide for BVI individuals. Similarly, an AR prototyping tool for creating interactive AR applications with arbitrary physical objects,*Teachable Reality* [Monteiro et al. 2023], also showed lack of accessibility considerations.

Our research uniquely integrates the three research key insights to bridge the gap between emerging technologies and inclusive education. Unlike prior research that focuses separately on technology, accessibility, and education, we combine successful elements from existing approaches and methodologies to address the practical implementation challenges that arise from recent AI-development and current limitations in VR/AR education tools.

3 Methodology

3.1 Scope and Selection Criteria

Our decision to focus on AR, VR, and other immersive technologies stems from their growing integration into various facets of life beyond entertainment, including lifestyle, educational, and accessibility contexts. In particular, VR has seen significant industry momentum, with several companies positioning it as a ubiquitous interface technology—on par with smartphones or headphones. This trend has been accelerated by recent surge in AI development, which increasingly enhances immersive platform capabilities. Given this convergence and the expanding research linking immersive technologies with education, our methodology emphasizes recent, technically substantive artifacts and literature reflecting these developments.

To guide our evaluation, we selected four focal technical artifacts that span a spectrum of accessibility integration and pedagogical intent:

Augmented Physics [Gunturu et al. 2024] is an educational tool that uses machine learning to convert static textbook diagrams into interactive physics simulations. Introduced at the 2024 ACM Symposium on User Interface Software and Technology (UIST), we selected this artifact as it exemplifies state-of-the-art AR innovation in educational settings. However, its reliance on visual interaction without non-visual alternatives illustrates how accessibility is often a secondary consideration in such systems and reflects a persistent gap in inclusive design practices.

Envision Glasses [Envision 2023], in contrast to *Augmented Physics*, were developed with accessibility as a core design principle from the outset. These AI-powered wearable devices process visual information and convert it into spoken descriptions, allowing BVI users to independently navigate environments and access printed text. The development emphasized inclusive design principles to empower marginalized communities.

Toucha11y [Li et al. 2023] makes inaccessible public touchscreen kiosks operable by BVI users via smartphone-based interaction. The system uses a mechanical bot to translate gestures on a mobile interface to touchscreen commands, offering independent access without modifying the kiosk hardware [Li et al. 2023]. Although developed for public infrastructure, its principles—spatial targeting, haptic feedback, and layered interaction design—are highly transferable to educational touchscreen applications and suggest promising directions for inclusive VR/AR interfaces.

TangibleCircuits [Davis et al. 2020] introduces a novel, tactile approach to STEM education. Leveraging 3D-printed circuit models and audio feedback, it enables no visual, independent exploration of electronic components. While not an immersive AR system, *TangibleCircuits* deals with similar challenges such as spatial representation, multimodal interaction, and affordability, making it a valuable reference for designing non-visual supported education hardware and content.

3.2 Evaluation Framework

To conduct a structured analysis, we evaluated each technical artifact through two complementary lenses: (1) developer intent and context, and (2) alignment with accessibility research and inclusive design literature.

For the first lens, we conducted a qualitative analysis of publicly available resources such as academic publications, product websites, and interviews. By examining how the developers framed their technologies, including their problem statements, referenced literature, demographic backgrounds, and any explicit attention to accessibility, we aimed to understand how design decisions evolved in relation—or lack thereof—to inclusive practices. We therefore critically assess whether accessibility was an inherent part of the design process or treated as an afterthought. To structure our evaluation, key guiding questions included:

- What problem does the technology aim to solve?
- What prior work or communities are referenced?
- Is accessibility explicitly addressed, and if so, how central is it to the design?
- What interaction assumptions are made (e.g., reliance on vision or hand gestures)?
- Did the developers conduct their own user or accessibility research?
- How generalizable is the solution (e.g., are there dependencies on proprietary hardware or software)?

In parallel, we assessed the artifacts' alignment with contemporary accessibility literature by cross-referencing the design and functionality of each technical artifact with insights from our literature review. This included assessing whether the technologies addressed key accessibility challenges—such as spatial navigation or non-visual feedback—reflected gaps identified in previous studies, or contradicted established best practices in inclusive design. We examined how each artifact embodied, extended, or diverged from accessibility frameworks and best practices, especially those surfaced in systematic reviews. This comparative analysis enabled us to situate each artifact within broader scholarly discourse on inclusive education and HCI, surfacing areas where inclusive principles have been meaningfully integrated and where critical accessibility considerations remain underexplored.

3.3 Reviewing WCAG 2.2 for Immersive Learning

To systematically evaluate accessibility gaps in immersive educational technologies, we grounded our critique in the WCAG [W3C 2024], an established and foundational framework. WCAG offers four core principles—Perceivable, Operable, Understandable, and Robust (POUR)—that guide the design of accessible web content and offer structured vocabulary for evaluating interface accessibility. Each WCAG principle includes numbered guidelines, which describe high-level accessibility goals (e.g., 1. Perceivable), and specific success criteria (e.g., 1.4 Contrast, 3.3.3 Error Suggestion) These criteria are also assigned a conformance level—A (minimum), AA (mid-range), or AAA (highest)—which indicates the level of accessibility compliance required.

While WCAG 2.2 [W3C 2024] remains the most referenced version for its clarity and tooling support, it was designed for static, screen-based web content and falls short when applied to immersive, multi-sensory, or AI-driven environments. The framework assumes 2D interaction models like keyboard navigation and linear page structure, which do not align with the spatial complexity and dynamic feedback mechanisms of VR/AR systems. Given these constraints, we found that extending WCAG to better accommodate immersive learning was more pragmatic than designing a new framework entirely.

We began by identifying WCAG criteria most at odds with with the affordances of immersive systems, such as "Text Alternatives" (1.1) and "Focus Order" (2.4.3), which fail to account for spatial and gaze-based interfaces. We prioritized high-level categories like "Perceivable" and "Operable," incorporating sub-guidelines only when directly relevant to multi-modal contexts. Our revisions were grounded in WCAG documentation, accessibility research, and case studies, ensuring both technical accuracy and practical relevance. Reinterpreting guidelines required us to account for 3D space, gaze and gesture inputs, haptic/audio feedback, and platforms like *Unity* or *Unreal* rather than traditional HTML/CSS/JS stacks. The criteria most misaligned with these needs are summarized in Table 1.

3.4 Revising Guidelines for VR/AR Learning

Building on the limitations identified in Table 1, we initiated a structured revision process to prototype WCAG extensions tailored for immersive learning. Our goal was not to reject WCAG 2.2 [W3C 2024] principles, but to reinterpret them in a modality-agnostic way—preserving the underlying principles of the original guidelines while accounting for spatial navigation, non-linear interfaces, and multi-sensory feedback.

To ensure rigor, our revision process drew on both top-down and bottom-up methods. From the top down, we reviewed WCAG documentation [W3C 2024], including the rationale behind each criterion, to preserve its original intent. From the bottom up, we used insights gathered from our artifact evaluations, related case studies, and HCI course discussions. This hybrid approach allowed us to align accessibility theory with real-world design implications. We posed the following guiding questions during revision:

- What was the original design intent of this guideline, and how does it map to immersive environments?
- Does the criterion assume a screen-based, sequential layout incompatible with spatial interaction?
- Can the guideline be reinterpreted to include interaction modalities like haptics, gaze, voice, or spatial audio?
- Does the revision preserve or extend inclusivity without excluding underrepresented users?

Through this methodology, we developed a prototype framework designed to evaluate and support accessibility in immersive educational systems. Our adapted guidelines build on the strength of WCAG [W3C 2024] while addressing its limitations in spatial environments. This revised framework is introduced in Section 4, where it is applied to assess real-world artifacts and highlight persistent gaps in accessibility design for STEM learning tools.

Table 1. WCAG 2.2 guideline limitations and reinterpretation needs for VR/AR educational technologies

Criteria	Conf.	Original Guidelines Description	Case Study Remark and Critique
WCAG guideline 1.1: Perceivable: text alternative for non-text item	(A)	Provide text alternatives for any non-text content so that it can be changed into other forms people need, such as large print, braille, speech, symbols, or simpler language.	Text alternatives assume flat, screen-based content, but in VR/AR, text alone cannot convey 3D spatial features like depth or movement. Phrases like "a cube is in front" lack spatial fidelity, making this guideline insufficient in immersive contexts.
WCAG guideline 1.3.1: Perceivable: adaptable: information and relationship	(A)	Information, structure, and relationships conveyed through presentation can be programmatically determined or are available in text.	Assumes information relationships are conveyed via layout or markup. In VR/AR, they are defined spatially and through movement, not semantic hierarchy. The logic of "nearby" or "connected" is visual and kinetic, not textual.
WCAG guideline 1.3.2: Perceivable: adaptable: meaningful sequence	(A)	When the sequence in which content is presented affects its meaning, a correct reading sequence can be programmatically determined.	In VR/AR, content surrounds the user, often without a clear starting point, making linear sequence assumptions ineffective in spatial environments with multiple coexisting objects.
WCAG guideline 2.4.2: Operable: Page title	(A)	Web pages have titles that describe topic or purpose.	VR/AR environments are spatial, continuous, and experiential, so the notion of a "page" is largely irrelevant.
WCAG guideline 2.4.3: Operable: Focus order	(A)	If a web page can be navigated sequentially and the navigation sequences affect meaning or operation, focusable components receive focus in an order that preserves meaning and operability.	Focus logic in WCAG depends on sequential tabbing, while in immersive systems, users interact through gaze, gestures, or spatial controllers. Focus shifts dynamically based on user position and intent, not coded order.
WCAG guideline 2.4.6: Operable: Headings and Labels	(AA)	Headings and labels describe topic or purpose.	While labeling remains important, traditional heading hierarchies (e.g., H1–H6) do not map easily to VR/AR where size, position, and motion define importance.
WCAG guideline 2.4.8: Operable: Location	(AAA)	Information about the user's location within a set of web pages is available.	Static notions of location are insufficient in VR/AR, where user position is dynamic and content shifts continuously.
WCAG guideline 3.2.1: Understandable: Predictable: On focus	(A)	When any user interface component receives focus, it does not initiate a change of context.	Spatial focus is typically triggered by gaze, gesture, or controllers, not keyboards. New models for focus behavior are needed.
WCAG guideline 3.2.4: Understandable: Predictable: Consistent identification	(AA)	Components that have the same functionality within a set of web pages are identified consistently.	In AI-based technologies, interactions are dynamic and context-sensitive, making strict consistency across components difficult, especially for BVI users.
WCAG guideline 4.1.1: Robust: Compatible: Parsing	(A)	Note: Originally adopted to address assistive technology parsing HTML, now obsolete.	Valid HTML parsing is irrelevant to VR/AR development platforms like Unity or Unreal, where different data models apply.
WCAG guideline 4.1.2: Robust: Name, Role, Value	(A)	For all UI components, the name and role can be programmatically determined; user-settable properties and notifications must be available to assistive technologies.	Current VR/AR engines offer limited support for exposing role, name, or state information for spatial objects to assistive technologies.

4 Findings

4.1 Proposed Framework for Accessible Immersive Learning

Building on the critique outlined in the Methodology, we propose a modified framework that extends WCAG 2.2 [W3C 2024] criteria to better support accessibility in immersive learning environments. This framework reinterprets existing guidelines for spatial, multi-sensory, and dynamic interfaces typical of VR/AR/AI systems. Table 2 outlines the adapted criteria, which form the basis for our case study evaluation in the next subsection.

4.2 Applying the Framework: Case Study Evaluations

While initially evaluating the four selected artifacts using the WCAG 2.2 criteria [W3C 2024], we identified the limitations in their ability to capture the accessibility challenges in specific immersive learning environments that were not captured from the current guidelines. After building a new revised version shown in Table 2, we subsequently re-evaluated the same artifacts with particular focus on aspects lik non-visual control, spatial labeling, and multimodal error feedback, that shows the revised framework's improved ability to assess inclusive factors for BVI users in emerging education technologies.

1. Augmented Physics

When assessed against our proposed accessibility framework, *Augmented Physics* exemplifies the persistence of long-standing accessibility gaps in AR-based STEM tools. Over a decade after Dünser et al. demonstrated AR's interactive learning potential, little progress has been made in addressing the needs of BVI users [Dünser et al. 2012]. *Augmented Physics* relies exclusively on visual cues, animated transitions, and screen-based manipulation, failing to offer alternative sensory modalities—thus falling short on perceivable and adaptable content (Guidelines 1.1, 1.3.1, 1.3.2). Its input model depends on standard devices like a mouse or trackpad, lacks multimodal interaction support (2.1.1), and provides no accessible location feedback or adaptive focus (2.4.3, 2.4.8). Despite its interface stability, it provides no error reporting or recovery support (3.3.1)—features essential for robust accessibility. Built on *OpenCV* and Meta's *Segment Anything*, its custom pipeline exposes no semantic roles or metadata, violating Guideline 4.1.2 and disconnecting it from assistive ecosystems [Gunturu et al. 2024]. While its "image-to-simulation" pipeline demonstrates pedagogical innovation for sighted users, the system remains misaligned with inclusive modalities—echoing Quintero et al.'s (2019) finding that few AR studies address visual impairment [Quintero et al. 2019]. A promising enhancement would be to integrate wearable haptic feedback, such as the system proposed by Sultania et al. [Sultania et al. 2023], which converts visual data into real-time tactile cues. Doing so could help shift *Augmented Physics* away from a visual-first paradigm and reinforce accessibility as a foundational principle in immersive STEM education.

2. Envision Glasses

Envision Glasses [Envision 2023] were developed with accessibility at their core, specifically targeting users with visual impairments. Though not designed for education, they demonstrate reasonable alignment with revised guidelines. Notably, the glasses provide audio feedback about the user's surroundings (3.2.4), such as describing scenes or reading signs, and include real-time object recognition and search to support spatial navigation (2.4.3). However, their functionality is limited to audio output, lacking support for interpreting visual educational content such as graphs or equations (1.3.1). The device also does not support third-party assistive technologies or provide alternative content formats (1.1), and its core features—like the call function—are tied to proprietary software. By locking key features into closed systems, the device may unintentionally exacerbate accessibility gaps for economically disadvantaged users. To better conform to our framework, *Envision Glasses* would benefit from broader compatibility and a focus on generalized domains.

Table 2. Proposed reinterpretations of WCAG 2.2 guidelines for immersive learning environments

Criteria	**Conf.**	**Original Guidelines Description**	**Proposed Revision for Immersive Contexts**
WCAG guideline 1.1: Perceivable: text alternative for non-text item	(A)	Provide text alternatives for any non-text content so that it can be changed into other forms people need, such as large print, braille, speech, symbols or simpler language.	Provide multisensory alternatives for any non-text 3D or spatial content. Use textual descriptions, spatial audio, haptic feedback, tactile graphics, or simplified representations.
WCAG guideline 1.3.1: Perceivable: adaptable: information and relationship	(A)	Information, structure, and relationships conveyed through presentation can be programmatically determined or are available in text.	Support spatial and interactive relationships through programmatic access and/or multisensory cues, not just semantic or visual layout.
WCAG guideline 1.3.2: Perceivable: adaptable: meaningful sequence	(A)	When the sequence in which content is presented affects its meaning, a correct reading sequence can be programmatically determined.	Support meaningful spatial sequences or context-sensitive exploration paths using user position, orientation, and interaction patterns.
WCAG guideline 2.1.1: Operable: keyboard accessible	(A)	All functionality of the content is operable through a keyboard interface without requiring specific timings for individual keystrokes.	Ensure operability via various input types, including spatial controls, voice, gesture, and gaze—without requiring timed or path-specific actions.
WCAG guideline 2.4.3: Operable: Focus order	(A)	Focusable components receive focus in an order that preserves meaning and operability.	Enable flexible spatial navigation where focus order preserves both spatial logic and user intent. Support custom focus pathways.
WCAG guideline 2.4.6: Operable: Headings and Labels	(AA)	Headings and labels describe topic or purpose.	Convey topic and purpose through spatial hierarchy, audio cues, or multimodal signals—such as directional sound, vibration, or size—instead of just visual headings.
WCAG guideline 2.4.8: Operable: Location	(AAA)	Information about the user's location within a set of web pages is available.	Ensure real-time spatial location feedback is available in immersive environments via visual, audio, or haptic indicators.
WCAG guideline 3.2.1: Understandable: predictable: on focus	(A)	When any UI component receives focus, it does not initiate a change of context.	Ensure changes in context occur only after explicit multimodal confirmation or intentional triggers, supported with predictive explanation.
WCAG guideline 3.2.4: Understandable: predictable: consistent identification	(AA)	Components with the same functionality are identified consistently.	Consistently categorize and describe components across spatial contexts to support user comprehension and navigation.
WCAG guideline 3.3.1: Understandable: input assistance: error identification	(A)	Errors are identified and described in text.	Errors must be clearly identified and described using multiple modes—text, sound, or haptics—based on user preferences.
WCAG guideline 4.1.1: Robust: compatible: parsing	(A)	Note: Criterion originally focused on HTML parsing, now deprecated.	Ensure compatibility with non-DOM-based environments (e.g., Unity) and enable third-party assistive tech integration if needed.

3. Toucha11y

While not originally designed for educational contexts, *Toucha11y* demonstrates how accessibility principles can bridge interaction gaps for BVI users in touchscreen environments. It aligns closely with the revised WCAG criteria [W3C 2024], addressing multisensory alternatives (1.1) through tactile and auditory smartphone feedback that enhances perceptibility while maintaining familiar interaction. It effectively supports spatial relationships and context-sensitive exploration (1.3.1, 1.3.2), and its input methods (2.1.1) leverage accessible smartphone interfaces, enabling voice, gesture, and haptic interactions that overcome touchscreen barriers. Navigation and feedback are flexible and compatible with assistive technologies like screen readers (4.1.1). However, *Toucha11y*'s focus on static screens limits its adaptability to dynamic educational interfaces, raising future concerns around predictability and interface consistency (3.2.1).

4. TangibleCircuits *TangibleCircuits* emerges as a compelling example of inclusive STEM tool design. Created for BVI learners, it combines tactile 3D models with audio feedback to address perceivability and structural understanding (1.1, 1.3.1). Its support for spatial exploration via touch-triggered cues enables meaningful, context-sensitive interaction (1.3.2, 3.2.1). Operability is strengthened through physical inputs using conductive materials, removing reliance on screens and supporting alternative interaction modes (2.1.1, 3.2.4). Its automated parsing system converts standard diagrams into 3D-printable, audio-annotated tutorials, reducing educator burden while enhancing accessibility (4.1.1, 3.3.1). Although *TangibleCircuits* currently serves as a supplemental rather than standalone system, its approach demonstrates that accessible design can be both affordable and scalable, paving the way for multimodal alternatives in immersive education.

5 Discussion

Our findings reveal a persistent gap between technical innovation in immersive STEM tools and their practical accessibility for BVI learners. While systems like *Augmented Physics* and *Teachable Reality* advance pedagogical interactivity, they often do so at the expense of inclusive design—defaulting to visual-first assumptions and excluding non-visual modalities. These tools reflect a broader trend in VR/AR and AI-driven education tools where accessibility is addressed reactively, if at all.

Conversely, tools explicitly designed with accessibility for disabilities as a core principle, such as *Toucha11y* and *TangibleCircuits*, demonstrate that accessibility can be embedded meaningfully into design through multisensory interaction modes. However, they also highlight trade-offs: *Toucha11y* is not yet suited for dynamic content, and *TangibleCircuits* is supplemental rather than fully immersive. This tension underscores the need to balance generalizable educational value with specific accessibility practices.

These findings affirm the limitations of existing accessibility standards when applied to immersive systems and suggest the need for a new set of standards that accommodate the hurdles posed by emerging technology, particularly in the context of STEM education. Our proposed WCAG revisions offer a foundation for more context-sensitive evaluations, emphasizing spatial logic, real-time interaction, and multi-sensory representation.

Future development should actively involve BVI users through participatory design to ensure accessibility frameworks are not only theoretical but usable in practice, especially at the early stages of a design or development process. Expanding evaluations to a wider range of educational tools across diverse learning environments can also uncover universal design challenges and inform potential solutions for inclusive classrooms.

6 Conclusion

This study critically evaluated how emerging VR/AR/AI technologies in STEM education address accessibility for BVI learners. Using a revised WCAG-based framework, we demonstrated that while pedagogical innovation is accelerating, accessibility practices often lag behind. Our analysis highlights that inclusive design remains fragmented, with most tools offering either partial solutions or overlooking BVI needs entirely. To bridge this divide, we call for accessibility to be integrated from the outset—grounded in revised standards, informed by user needs, and driven by interdisciplinary collaboration among technology developers, accessibility experts, educators, and the BVI community. Only then can immersive education technologies equitably serve all learners.

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