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Aim and scope: To communicate and complete knowledge on ICT, AT and Accessibility for/with people with disabilities and older adults and connect research in these domains with the necessary practical background and user related aspects.

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Editorial

This fifth edition of the ICCHP Open Access Compendium "Future Perspectives on AT, Accessibility and (e)Inclusion" accompanies the scientific proceedings published in Springer's Lecture Notes in Computer Science by opening an additional, cross-domain space for dialogue. While the LNCS volumes primarily gather research in specific technical fields, the Open Access Compendium brings together contributions that link these advances to broader questions of accessibility, inclusion, and technology in practice.

The contributions collected in this compendium connect research outcomes with educational settings, social policies, user organizations, and everyday environments. They highlight how assistive technologies and accessible design become meaningful when they are embedded in inclusive infrastructures, institutional frameworks, and participatory processes. In this way, the compendium not only complements the LNCS proceedings: it extends the view from specialized domains to the interfaces between disciplines, sectors, and communities.

As editors, we are grateful to present contributions that connect research, practice, and lived experience in a shared commitment to accessibility and participation.

The publications in this volume highlight assistive technologies as part of broader social, educational, and digital transformations rather than stand-alone technical fixes. Authors explore how accessibility can be built into infrastructures and services from the outset, addressing questions of usability, standards, ethics, and sustainability.

Education and capacity-building are central themes, with chapters on inclusive teaching strategies, accessibility-oriented curricula, and professional development. These works demonstrate that expertise in AT and (e)inclusion grows through long-term collaboration among educators, technologists, policymakers, and user communities.

Further contributions present innovative applications in communication, mobility, digital interaction, and support for diverse disabilities and neurodivergent profiles. They offer prototypes, empirical studies, and frameworks that translate conceptual advances into concrete practices.

Legal, policy, and socio-economic analyses underline that inclusive futures depend on coherent regulation, sustainable funding, and meaningful user involvement in decision-making. Together, the publications gathered here invite readers to see AT and accessibility as core elements of democratic societies that value dignity, autonomy, and the right to belong.

So, take this ICCHP and make it to your event, your place to learn, present and network

Come and get involved - Stay to shape the future!



Andrea Petz



Klaus Miesenberger



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STS

Accessible and Inclusive Digital Publishing

Mapping Accessibility by Design in Editorial Front-End Development: A Comparative Study Between Norwegian and Italian Publishing Houses

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Abstract

Digital accessibility is frequently deferred to late development phases, generating rework and persistent barriers for users with disabilities. This paper presents a qualitative comparative case study examining how accessibility is operationalized within front-end development workflows at two educational publishing houses: Aschehoug (Norway) and Zanichelli Editore (Italy). Eleven semi-structured interviews with front-end developers and designers were conducted, and five dimensions were analyzed: regulatory embedding, process integration, responsibility distribution, evaluation practices, and knowledge and expertise. Findings reveal that Norway's decade-long enforcement history produces earlier accessibility integration, higher internal confidence, and more systematic evaluation. Italy's recent exposure to the European Accessibility Act results in a reactive, post hoc model reliant on external audits. Crucially, a structural gap between automated compliance and experiential accessibility is shared across both contexts, and systematic testing with real users with disabilities is achieved in neither. The study contributes process-level evidence to inform accessibility-by-design practices in the editorial publishing sector.

Introduction

Digital accessibility is increasingly recognized as a core quality attribute of digital systems, yet in practice it remains rarely treated as a first-class design concern. Instead, it is commonly deferred to downstream verification activities, leading to costly rework cycles and persistent usability barriers for users with disabilities [1, 2]. This misalignment is particularly consequential in the educational publishing sector, where interactive learning content, complex front-end architectures, and frequent platform updates amplify the impact of accessibility-related decisions made, or neglected, early in the development process [3, 4].

The regulatory landscape governing digital accessibility is undergoing significant transformation in Europe. With the European Accessibility Act (EAA) [7] entering into force in June 2025, private-sector organizations across EU member states are now required to meet established accessibility standards. However, many organizations face this obligation without established processes or internal competencies capable of supporting accessibility by design. This situation is not uniform across Europe: countries such as Norway have enforced accessibility and Universal Design requirements for both public and private sectors since 2013, enabling earlier institutionalization of inclusive development practices.

Recent cross-national benchmarks further signal these disparities. The Digital Trust Index 2025, based on large-scale automated testing of European website homepages, consistently ranks Norway at the top, while Southern and Eastern European countries, including Italy, appear in the lower-ranked group [5]. The Education & Science sector recorded a failure rate of 91.79% across 13,129 tested pages [5]. While these results are limited to surface-level automated checks and do not capture interaction quality or assistive technology compatibility, they motivate a deeper investigation into how accessibility is operationalized within front-end workflows under different regulatory histories.

This paper addresses that gap through a comparative case study of two educational publishing houses: Aschehoug, based in Norway and operating under a mature regulatory framework, and Zanichelli Editore S.p.A., based in Italy and confronting private-sector accessibility obligations more recently under the EAA [7]. By examining concrete development practices, responsibility allocation, and decision-making timing, this study aims to identify the process-level factors that differentiate accessibility integration across organizational and regulatory contexts.

Related Work

Accessibility in software engineering processes

Accessibility in software engineering processes. Existing literature consistently documents a gap between accessibility awareness and its systematic integration into software development workflows. Paiva et al. [3] found that accessibility is frequently treated as a compliance obligation rather than a quality-driven design attribute, resulting in fragmented responsibilities and validation activities concentrated in late development phases. Springer et al. [4] similarly observed that accessibility assessments are often disconnected from iterative design cycles and rarely influence architectural or component-level decisions.

Developer practices and tool limitations

Empirical investigations reveal significant structural limitations in how developers engage with accessibility. Bi et al. [1] found that developers frequently lack clear ownership and tend to address it reactively. Alghamdi et al. [6], analyzing Stack Overflow discussions, found that developer challenges cluster around behavioral and interaction-level requirements, suggesting complexity well beyond what automated tooling can surface. Nie et al. [2] corroborate this, demonstrating that automated tools cover only a narrow subset of accessibility issues, leaving dynamic content, complex interactions, and assistive technology behavior largely unaddressed.

Regulatory context and cross-national variation

Taken together, these studies suggest that accessibility shortcomings are less attributable to individual skill deficits and more closely linked to how development processes structure ownership, decision timing, and validation activities [4]. However, limited empirical work has examined how these factors manifest within editorial front-end development, and no comparative studies have been conducted across organizations operating under substantially different regulatory histories. This study addresses that gap directly.

Norway was among the first countries to introduce enforceable ICT accessibility requirements covering both public and private sectors. The Anti-Discrimination and Accessibility Act of 2008 introduced legal safeguards across all sectors [8], followed by specific ICT regulations taking effect in 2013 and requiring universal design compliance from 2014 [9], supervised by the Norwegian Authority for Universal Design of ICT [10]. Italy's path was narrower and later. The Stanca Act (Law 4/2004) was originally limited to the public sector [11], extended to large private companies through the 2020 Decreto Semplificazioni [12]. Italy's EAA transposition, Decreto Legislativo n. 82/2022, requires newly bound private entities to comply by June 2025 [13].

Methodology

This study adopts a qualitative comparative case study design, selecting two educational publishers as contrasting cases: Aschehoug (Norway) and Zanichelli Editore (Italy). The cases were chosen to represent substantially different regulatory trajectories, enabling investigation of how regulatory maturity relates to accessibility integration within front-end development workflows.

Eleven semi-structured interviews were conducted with front-end developers and designers directly involved in product development: four developers and one designer at Aschehoug, and four developers and two designers at Zanichelli Editore. Interviews followed a structured protocol covering four thematic areas: role and workflow, accessibility integration, testing and evaluation, and knowledge and training. All sessions were recorded, transcribed, and anonymized; participant identifiers follow the format NO-01 through NO-05 and IT-01 through IT-06.

The unit of analysis is the front-end development workflow, with focus on how accessibility-related decisions are introduced, distributed among roles, and evaluated across the development lifecycle. Data were analyzed through thematic coding combining deductive and inductive approaches, structured around five dimensions: regulatory embedding, process integration, responsibility distribution, evaluation practices, and knowledge and expertise.

Results

Regulatory Embedding

In Norway, the regulatory framework is perceived as a concrete, non-negotiable mandate backed by active governmental enforcement. The most tangible enforcement mechanism is the system of daily financial penalties imposed by law for non-compliant products. NO-05 confirms that Aschehoug underwent government audits in 2022, consequently prioritizing the most critical issues identified.

At the same time, regulatory stringency introduces operational tensions. NO-04 describes having to abandon interactive educational features when no accessible implementation could be identified. Norwegian educational publishers collectively attempted to negotiate more flexible WCAG interpretations with the relevant authorities, without binding outcome. NO-01 illustrates a concrete case: providing alternative text for every speech bubble in digital comics was deemed functionally impractical, a content type both the EAA [7] and Norwegian regulation [9] explicitly recognize as exempt.

The Italian regulatory context presents a markedly different configuration. Participants acknowledge awareness of the EAA, but this has not yet translated into institutionalized pressure. The Italian authority responsible for accessibility oversight has not yet initiated formal audit procedures, and the regulatory landscape is widely described as still taking shape. Italian participants predominantly ground their motivation in professional ethics and user-centered design values rather than legal or commercial drivers. IT-05 explicitly states that he perceives neither legal nor commercial pressure, preferring to approach accessibility through design sense. IT-03 offers a more nuanced view, acknowledging that formal compliance requirements do not always map onto what users with disabilities actually need

Process Integration: Design Constraint vs. Post Hoc Evaluation

The Norwegian case

Accessibility as a design constraint. In the Norwegian context, accessibility functions as a design-time constraint. NO-02 describes addressing component-level accessibility from the very beginning of implementation: shared components are tested with Axe DevTools, Chrome's native tools, and screen readers before publication, so that downstream teams inherit compliant elements by default. NO-05 integrates accessibility into the formal QA checklist completed prior to deployment, and NO-04 incorporates it directly into the coding phase. As NO-02 puts it: "If you think about it from the beginning, in the design and early development phase, it's much easier and more efficient". This model is not uniformly distributed across Aschehoug. NO-03 constitutes an instructive exception: the platform she works on was built without systematic accessibility consideration and remains deprioritized, as the product owner has never formally requested it, in part because it targets a professional context where accessibility expectations have been less pronounced than in the public and educational sectors.

The Italian case: accessibility as a post hoc evaluation requirement

The Italian context reflects a late-stage integration model. IT-03 explicitly states that testing "is always done in the final phase." IT-02 describes both external audits and AI-assisted checks as occurring in the production phase, characterizing this as "too late," and expressing a preference for integrating testing at the pull request stage. IT-06 describes a workflow in which accessibility is assumed to be inherited from the Design System rather than actively verified. Italian design handoffs tend to address visual accessibility properties (color contrast, typography, element sizing) while leaving interaction-level concerns to be resolved during implementation. IT-01 describes efforts to bridge this gap by annotating focus order and heading hierarchies within Figma files before handoff.

External collaboration vs. internal confidence. Italian teams rely systematically on external audit providers as the primary mechanism for identifying and remediating issues, and as an informal learning channel. However, different providers may offer divergent recommendations, generating interpretive uncertainty. IT-03 describes receiving directly contradictory prescriptions from different auditors on the same ARIA labeling issue, an inconsistency she characterizes as the most debilitating aspect of her accessibility work.

Responsibility Distribution

Both organizations employ a Design System as the primary mechanism for distributing accessible components across product teams, on the premise that consuming teams inherit accessibility without additional effort, a point of structural convergence across NO-02, IT-01, IT-02, and IT-06.

However, Design System maturity differs substantially. Aschehoug maintains a React-based component library documented through Storybook, with each component subjected to automated and manual testing prior to publication. The Zanichelli Design System is described by IT-01 as a work in progress, with accessibility documentation added incrementally. IT-06 acknowledges that his team does not systematically test how components behave in real application contexts, trusting that accessibility is preserved without verifying it.

Both groups recognize a shared structural risk: a component accessible in isolation can become inaccessible when combined with others. IT-06 illustrates this with a select component that lost its accessibility properties when a tree structure was added; IT-01 describes a comparable case where focus order errors emerged only during implementation. NO-02 notes that automated regression testing is used to detect such degradation.

The designer-developer responsibility boundary follows a similar pattern in both contexts: designers address the visual layer while developers handle the technical layer. This boundary is a frequent source of gaps when handoffs lack explicit interaction-level specifications. Both NO-01 and IT-01 describe efforts to bridge it, the former by aligning the Figma Design System with front-end implementations, the latter by adding focus order and heading annotations to handoff files.

Evaluation Practices

Evaluation practices exhibit notable similarities in tooling but diverge substantially in temporal integration. Practitioners in both contexts also identify a persistent gap between automated compliance measurement and real-world usability.

Shared reliance on automated tools

Both contexts rely extensively on automated evaluation tools. Italian teams employ Wave, Axe, Lighthouse, and Accessibility Insights, alongside the Figma plugin Stark, and are increasingly adopting an AI solution for automated code scanning and pull request generation. IT-02 considers the AI solution more actionable than traditional audit providers, though its current deployment at the production stage limits its preventive utility. Norwegian teams use a comparable suite including Wave, Siteimprove, Axe DevTools, and native Chrome accessibility utilities.

The Norwegian case: iterative and continuous evaluation

In Norway, evaluation is distributed across the entire development lifecycle. NO-02 tests components using screen readers and browser plugins during active code authoring. Shared components undergo automated and manual testing from the earliest stages of creation. NO-05 confirms that accessibility checks are part of the formal QA checklist completed before code is merged, institutionalizing evaluation as a standard gate rather than an optional activity.

The Italian case: episodic and late-stage evaluation

In Italy, evaluation is concentrated at the terminal stages of development, with internal manual testing occurring only upon completion of individual tasks or user stories. Formal external audits are infrequent and often conducted on code already in production. This configuration introduces significant inefficiencies: one practitioner reported receiving an audit report six weeks after submission, by which point the audited codebase had already been entirely superseded. The lateness of evaluation and the slowness of external feedback thus combine into a structural inefficiency that concretely limits teams' ability to intervene in a timely manner.

The gap between measurable compliance and experiential accessibility

Across both contexts, practitioners express frustration that evaluation practices focus on surface-level, readily detectable issues at the expense of capturing how assistive technologies perform during complex interactions. Italian developers note that automated tools are reliable for discrete checks, such as missing alternative text, but largely ineffective for evaluating navigation flows or interaction-level behavior. IT-02 observes that they cannot capture the experiential dimension of how a blind user navigates a product. Norwegian practitioners echo this: NO-05 reports that an audit conducted by users with disabilities revealed critical navigation failures that had gone entirely undetected by the internal team's technical testing.

Knowledge and Expertise

A consistent finding across all eleven interviews is that digital accessibility was not formally taught in any educational curriculum, in either country. IT-03 characterizes it as "dark matter," entirely unknown before joining Zanichelli. NO-03 confirms it "was not learned at school or at university." In both contexts, knowledge has been acquired through practice, organizational exposure, and peer mentorship rather than structured professional formation.

Despite this shared origin, trajectories differ substantially. Norwegian participants report earlier and more sustained engagement: NO-02 has worked with accessibility for approximately ten years; NO-01 traces her first engagement to around 2010, when the shift from Flash to responsive design made it a practical concern; NO-04 has engaged with it from his first day, given the legal obligation in force since 2013. NO-03 developed her knowledge under the mentorship of a senior developer, reflecting an environment in which accessibility knowledge is actively transmitted through collegial practice. Italian participants report more recent and concentrated engagement, predominantly within the last two to three years, driven by organizational initiatives, external audit relationships, AI-assisted tooling, and the regulatory momentum of the approaching EAA deadline.

Conclusion and Future Work

This study examined how digital accessibility is operationalized within front-end development workflows in two educational publishing houses operating under substantially different regulatory histories. The findings reveal that regulatory maturity translates into measurable process-level differences: the Norwegian context, shaped by over a decade of enforceable requirements, shows earlier integration of accessibility, higher internal confidence, and more systematic evaluation practices. The Italian context, confronting broader private-sector obligations more recently, reflects a late-stage integration model in which accessibility remains largely reactive, externally validated, and procedurally fragmented.

Crucially, both contexts share a structural gap between automated compliance measurement and experiential accessibility, and neither has achieved systematic testing with real users with disabilities. These findings suggest that regulatory pressure alone is insufficient to guarantee accessible-by-default development practices: organizational governance, design system maturity, and knowledge transmission within teams are equally consequential variables. Future work should expand the participant sample to include additional organizations and roles, particularly product owners and content designers, whose influence on accessibility integration emerged as significant. Longitudinal investigation would allow observation of how Italian teams evolve their practices as EAA compliance obligations take full effect. Finally, the universal absence of structured user testing with people with disabilities across both contexts points to a critical area for both research and practice: developing scalable models for integrating experiential accessibility evaluation within editorial front-end workflows.

Acknowledgments

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AI-Enhanced Immersive Media Environments: User-Centred Design and Participatory Practices

A Within-Subjects Evaluation of VR Interface Among Users with Motor, Visual, Auditory, and Neurological Impairments

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Abstract

This study evaluates the accessibility of three virtual reality interaction modalities: controller-based interaction, controller-free hand tracking, and passive 360° content. A within-subjects study was conducted with 19 participants with motor, visual, auditory, or neurological limitations using a Meta Quest 3 headset. Although no statistically significant differences were observed in System Usability Scale (SUS) scores between modalities, descriptive trends indicate lower perceived usability for hand tracking compared to controller-based interaction and passive content. Workload assessment using the NASA Task Load Index (NASA-TLX) reveals higher cognitive workload for hand tracking, particularly in physical demand and frustration. Qualitative findings identify frequent interaction breakdowns due to missing haptic feedback, neck strain related to headset ergonomics for wheelchair user, and discomfort reported by female participants. Sudden camera motion in 360° content caused vestibular conflict and safety concerns for users with limited mobility. While sensory responses varied, including reports of overload, one participant with severe myopia reported enhanced visual clarity. Overall, the results indicate that despite the inclusive potential of virtual reality, current hardware and interaction paradigms introduce systemic accessibility barriers.

Introduction

Virtual Reality (VR) is an immersive, computer-simulated environment that allows users to interact with digital surroundings as if they were in the physical world [1]. However, it creates significant barriers when it requires physical abilities that exclude large segments of the population [2,3]. Approximately 16% of the global population lives with a disability [4], meaning over a billion people are potentially excluded from these experiences [3]. Accessibility must be understood not merely as a response to health conditions, but as the attribute of being open to everyone, achieved through inclusive design [5].

Despite growing literature on VR accessibility [2], a critical gap remains regarding how users with diverse, intersecting impairments navigate standard, commercially typical interfaces. To address this, we quantify usability disparities by exploring the following primary research question (RQ): How do standard VR interfaces and specific interaction modalities (controller-based, hand-tracking, and passive 360° content) impact usability, cognitive workload, and accessibility barriers for users with diverse functional limitations?

The remainder of this paper is structured as follows. Section 2 reviews related work on VR accessibility, Section 3 describes the study methodology, Section 4 presents the results, Sections 5–6 discuss design implications, and Section 7 concludes the paper.

Background

The expansion of VR exposes a growing mismatch between mainstream immersive interface design and the needs of diverse users [2], as existing accessibility standards such as the Web Content Accessibility Guidelines (WCAG) [6] address two-dimensional interfaces but fail to account for embodied and spatial interaction demands inherent to VR [3]. Unlike conventional digital systems that abstract

interaction into simple inputs, VR frequently requires full-body sensorimotor engagement, substantially increasing barriers to entry for users with physical, sensory, or cognitive impairments [7].

For users with visual impairments, VR remains challenging due to visually dominant interaction paradigms and fixed-focus headset optics that do not accommodate common ocular conditions [8], although prior work shows that content-level adaptations such as magnification and contrast enhancement can significantly improve accessibility without optical correction [9, 10]. Complementary studies demonstrate that audio-based interaction and alternative locomotion techniques enable effective non-visual navigation and spatial understanding in immersive environments [11, 12].

Auditory accessibility research demonstrates that immersive captioning and transcription embedded in three-dimensional space improve comprehension and usability for deaf and hard-of-hearing users [13], that sign language learning and communication benefit from spatial and embodied virtual representations [14], and that multimodal and audio-centric VR applications enable sound to function as a primary information channel rather than a supplementary aid [15].

Users with mobility impairments encounter physical barriers resulting from headset weight, controller ergonomics, and interaction techniques that assume standing balance and extended reach [16], while obstructing visual access to the physical environment further increases postural instability for users who rely on visual cues [17]. Wheelchair users are additionally exposed to increased neck and shoulder strain during prolonged seated VR use [18], although software-based alternatives such as virtual reach adjustment and simplified interaction techniques reduce physical demand while preserving task performance [19].

VR also presents accessibility challenges and opportunities for neurodivergent users, as sensory-regulated environments can reduce overload when visual density and interaction complexity are carefully controlled [20]. For individuals with Autism Spectrum Disorder (ASD), reducing visual clutter improves attentional filtering and visuomotor integration [21], while immersive and distraction-controlled VR environments have been shown to increase sustained attention, motivation, and task engagement in individuals with Attention Deficit Hyperactivity Disorder (ADHD) [15, 22].

Despite extensive research across sensory, motor, and cognitive accessibility, prior work largely examines isolated impairment categories [17, 22], specialized therapeutic systems [20, 21], or accessibility tools [10, 14, 15], leaving a lack of empirical evidence describing how users with heterogeneous impairments experience standard VR interfaces. Establishing this baseline is critical to identifying systemic accessibility barriers embedded in mainstream VR interaction paradigms rather than framing accessibility as a collection of individualized accommodations.

Methodology

Participants

This study involved 19 participants (N=19; 9 female, 10 male) aged 18-55 with documented motor, visual, auditory, or neurological functional limitations. They were recruited in collaboration with the Academic Support Unit at Lodz University of Technology. All participants provided informed written consent acknowledging the study's voluntary nature, potential VR-related risks, continuous safety monitoring, and the use of anonymized data. Detailed participant demographic and functional profiles were collected prior to the session using a comprehensive pre-study questionnaire. Participants' educational backgrounds varied widely, including high school diplomas (n = 8), bachelor's (n = 1), master's (n = 8), and doctoral degrees (n = 2), ensuring a diverse sample in terms of general digital literacy. While participants reported high familiarity with standard digital devices, their prior experience with VR was predominantly non-existent or limited to sporadic usage. Given the sample's heterogeneity, we adopted an exploratory approach. Rather than comparing specific impairment subgroups, we aggregated quantitative data to evaluate overall usability across the user spectrum. Participants included

individuals with visual, motor, and neurodivergent conditions, alongside two with auditory impairments. This broad inclusion reflects the general consumer base and allows for the identification of universal accessibility barriers. Table 1 presents a detailed functional profile for each participant.

Table 1 Participant Functional Profiles

Group	ID	Sex	Age	Functional Limitations and Conditions
Visual Impairments	P01	F	18-25	Congenital vision defect, astigmatism, reduced acuity (-4.5/-0.75D)
	P02	M	18-25	Mild astigmatism
	P03	F	18-25	Vision defect, mild astigmatism, strabismus
	P05	M	26-35	Glaucoma and astigmatism (-1.5D both eyes)
	P07	F	18-25	Astigmatism and amblyopia (-1.75/+1.5D)
	P12	M	26-35	Severe high myopia (-19D), astigmatism, narrowed visual field; used -13D glasses during study
Motor and Mobility	P06	M	18-25	Wheelchair user, limited hand dexterity, tremors, photophobia; used tinted glasses during study
	P08	M	36-45	Spinal cord injury (wheelchair user)
	P13	F	36-45	History of 4 spine surgeries (mobility issues); motion sickness
	P14	F	18-25	Multiple Sclerosis (MS), balance issues, vertigo, astigmatism
	P15	F	46-55	History of several spinal surgeries, uses cane, right hand paresis, mild vision issues
	P17	F	46-55	Meniere's disease (balance issues), myopia, astigmatism
Neurodivergent	P04	M	26-35	ADHD, astigmatism (-2.75/-2,5D)
	P09	M	26-35	ADHD; left-handed
	P11	F	26-35	ADHD, significant anisometropia, astigmatism, labyrinth disorders
	P16	M	18-25	ASD, ADHD
	P18	M	18-25	ADHD
Auditory Impairments	P10	M	36-45	Hard of Hearing, non-sign language user
	P19	F	46-55	Profoundly deaf, utilizes sign language and lip-reading

Apparatus, Procedure, and Analysis

The study utilized the Meta Quest 3 to test three modalities: controller-based interaction, controller-free hand-tracking, and passive content consumption, with task order counterbalanced using a Latin Square design. Active tasks used *First Steps with Hand Tracking* (v1.0.920500) [23], requiring fine motor actions (stacking blocks, throwing planes, piloting an airship) and dynamic spatial interactions (dual-wielding pistols, dancing). The passive condition featured a YouTube VR 360° video - the Primorsky Safari Park [24]. The video featured a suspended camera perspective and sudden, dynamic motion, to evaluate how standard consumer media impacts users with physical and sensory vulnerabilities.

Data collection combined quantitative assessments with qualitative insights. Participants completed the System Usability Scale (SUS) and the NASA Task Load Index (NASA-TLX) immediately following each task to measure perceived usability and cognitive load. The session concluded with a semi-structured interview. Quantitative data were analyzed in JASP (v0.96.0.0) using descriptive statistics and non-parametric tests (Friedman ANOVA and Wilcoxon signed-rank). Sessions concluded with semi-structured interviews (mean duration: 9 minutes, range: 6 to 17 minutes) to compare modalities and contextualize

scores. Audio recordings were transcribed via Gemini 3.1 Pro and evaluated using thematic analysis [25] to identify recurring patterns regarding specific accessibility barriers, frustration points, and interface elements that caused discomfort.

Results

Quantitative Results

Analysis of SUS scores indicates that both controller-based (Mdn = 82.5, IQR = 16.25) and passive 360° modalities (Mdn = 82.5, IQR = 18.75) achieved high usability ratings, well above the established acceptability benchmark of 70 [26]. In contrast, the controller-free hand-tracking modality recorded a lower score (Mdn = 65.0, IQR = 32.5) with a notably wider dispersion, dipping into ranges associated with severe usability problems (Min = 27.5). However, a Friedman test revealed this variance across tasks was not statistically significant, χ^2 (2, N = 19) = 5.452, p = .065, W = 0.143. While descriptive trends suggest hand-tracking introduces distinct interaction barriers for certain individuals, the lack of overall significance highlights the highly individualized nature of VR accessibility, where a single interaction method can be perfectly usable for one person but entirely inaccessible for another.

Regarding perceived workload, a Friedman test demonstrated a statistically significant difference in NASA-TLX scores across the three tasks, χ^2 (2, N = 19) = 14.43, p < .001, W = 0.380. Post-hoc pairwise comparisons using Wilcoxon signed-rank tests with a Bonferroni correction (adjusted α = .0167) revealed significantly higher workload for hand-tracking compared to both the controller-based task (W = 12.50, z = -3.320, p < .001, r_B = -0.868) and the passive 360° task (W = 145.5, z = 2.613, p = .010, r_B = 0.702). Workload differences between the controller-based and passive tasks did not reach significance (W = 147.0, z = 2.093, p = .036, r_B = 0.547).

Figure 1 shows higher median NASA-TLX scores and wider IQRs for hand tracking across most subscales, indicating greater workload. Mental Demand varied widely across all modalities, potentially due in part to discomfort caused by the camera height in the passive 360° video reported by several users. Whereas Frustration, Effort, and Performance were consistently low and less dispersed for controller-based and passive tasks.

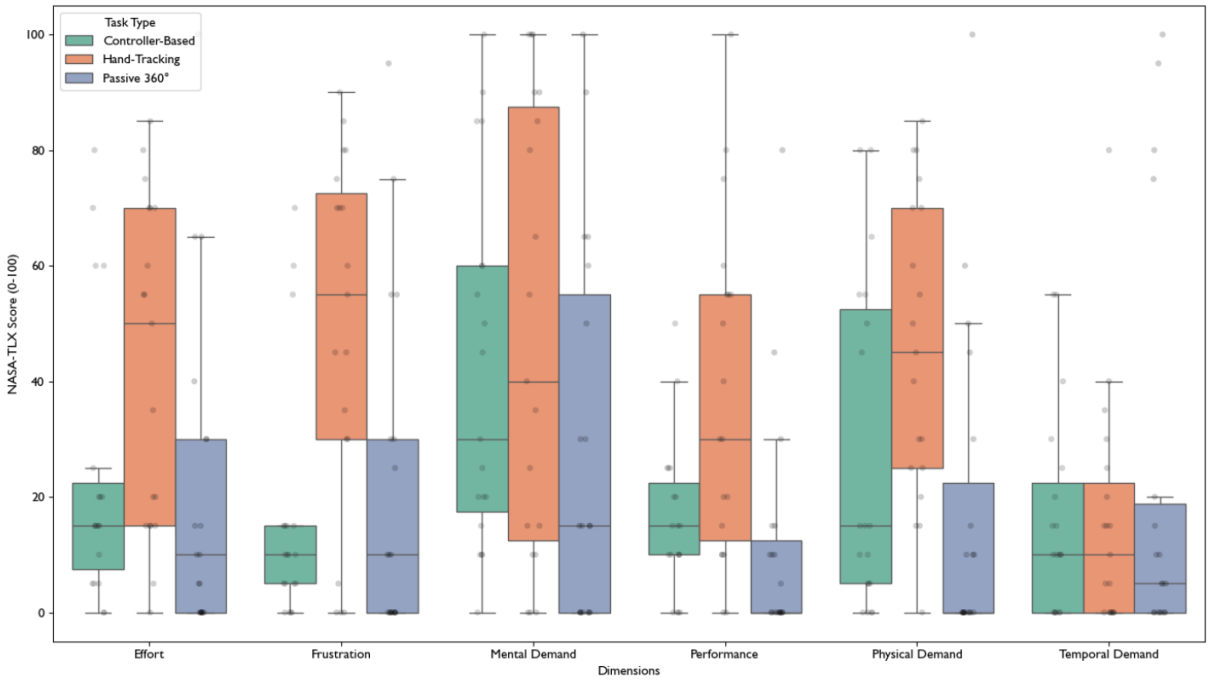


Figure 1 Distribution of NASA-TLX subscale scores.

Qualitative Insights

Post-task interviews and in-situ observations revealed recurring accessibility barriers.

Input Modalities: Hand-Tracking vs. Controllers.
Almost all participants experienced interaction breakdowns using hand-tracking due to a lack of physical resistance and exaggerated force requirements. Every participant except P12 (a daily drone operator) failed the airship task with hand-tracking. P17 described grasping empty air as "annoying" compared to the tactile feedback of physical buttons. While hand-tracking felt less restrictive for expressive tasks like dancing, participants P13 and P17 explicitly required controllers for precision tasks like shooting. For users with auditory impairments (P10, P19), controllers served as crucial output devices, substituting sound with haptic vibration to convey rhythm. Neither user experienced physical conflicts between the headset and their hearing aids. P10 noted his primary barrier was mastering the physical controllers rather than audio limitations.

Output Modalities: Ergonomics and Visual-Vestibular Conflicts
Visual limitations did not present as many barriers as expected. Participants successfully wore prescription glasses without physical conflict (P06, P12, P14), and P12 (severe myopia) reported exceptional image clarity. However, software-level legibility proved problematic during the passive video task. Subtitles were small, unanchored, and frequently drifted out of the field of view, while high-contrast white text on a black background caused visual fatigue (P19).

Hardware ergonomics introduced distinct physical roadblocks. The headset fit poorly for several female participants (P11, P14, P17), causing cheekbone pain, and its front-heavy weight induced immediate neck strain for a wheelchair user (P06). The spatial layout of virtual consoles further excluded users based on mobility. Fixed at a normative standing height, the interface obstructed the field of view for seated users (P06, P08, P14, P15) and forced awkward upward interactions, yet remained too low for taller standing participants (P04, P12, P16).

The passive 360-degree video exposed severe visual-vestibular conflicts. Suspended camera perspectives and sudden movements induced dizziness and posed direct safety risks for users with limited trunk control; the sensation was intense enough that one wheelchair user (P08) instinctively checked his physical brakes. Sensory overload and distraction also varied widely. P16 found the initial concurrent stimuli overwhelming. Participants with ADHD (P04, P09, P11, P16) struggled to remain stationary during passive content, frequently wandering or checking menus. Task-related distraction directly impacted gameplay, as repeatedly dropping the virtual weapon severely demotivated P04.

Discussion

The accessibility of VR environments depends heavily on interaction modalities and hardware design. In this study, controller-free hand tracking introduced significantly increased subjective workload compared to controller-based interaction and passive 360° viewing. This pattern is consistent with participant reports of frequent interaction breakdowns and elevated physical demand and frustration, suggesting that mid-air gestures can amplify cognitive and motor effort, especially for users with diverse functional limitations.

Qualitative findings revealed severe ergonomic mismatches that function as structural accessibility barriers. Several female participants reported poor headset fit and discomfort, aligning with Stanney et al. [27], who note VR headsets are frequently designed using male-specific anthropometric data. Additionally, the front-heavy design induced immediate neck strain for a wheelchair user. As Sabari et al. [18] who demonstrate that wheelchair users rely heavily on head and neck movements for functional task performance and may therefore be highly susceptible to fatigue from heavy head-mounted displays.

While the headset optics accommodated severe myopia for one participant, software-side legibility remained a recurring barrier, particularly during the passive video task. Small, unstable subtitles

frequently drifted out of view, highlighting the need for anchored, adjustable text. Furthermore, the passive 360° video exposed severe vestibular conflicts that kept NASA-TLX Mental Demand scores high despite the lack of active interaction. Suspended camera perspectives induced height-related dizziness, while sudden movements caused direct balance and safety concerns for users with limited mobility. This reinforces Ferdous et al. [17], who report that blocking visual access to the physical environment in VR can increase postural instability for users with balance impairments.

Unconstrained environments and interaction friction also impacted engagement for neurodivergent users. Repeated hand-tracking failures became a persistent distractor for some participants, while passive viewing prompted frequent menu checking and difficulty remaining stationary among participants with ADHD. This aligns with Gaggi et al. [15] and Cuber et al. [22], who emphasize that VR can support concentration for individuals with ADHD only when interaction friction and external distractions are actively minimized. Similarly, participants on the autism spectrum reported rapid overload during visually dense application introductions, consistent with evidence that carefully regulated sensory environments and reduced visual clutter support attentional filtering and visuomotor integration in autistic individuals [15, 21].

Design Recommendations for Inclusive VR

1. Based on the empirical and qualitative findings, the following actionable guidelines are proposed to improve VR accessibility:
2. Input Flexibility: Support seamless switching between controllers and hand-tracking, augmenting the latter with distinct audio-visual cues to replace missing haptics.
3. Spatial Adjustability: Allow users to vertically adjust all UI elements and securely anchor menus to the center of the visual field to accommodate seated mobility.
4. Sensory Regulation: Implement low-sensory modes or graduated onboarding to minimize visual clutter and audio intensity for neurodivergent users.
5. Stable Camera Perspectives: Ground camera angles in 360-degree media and eliminate unpredictable movements to prevent vestibular conflicts and physical instability.
6. Dynamic Legibility: Stabilize floating text and provide fully adjustable spatial placement, font sizing, and background contrast.

Conclusions and Possible Next Steps

While this study provides critical insights into immersive accessibility, several limitations inform future research. The participant sample (N=19) was deliberately heterogeneous to identify universal accessibility barriers across a general consumer base. However, this diversity precludes deep statistical comparisons between specific impairment categories. Future studies should recruit larger, condition-specific cohorts to build upon these baseline findings. Furthermore, the evaluation used a single introductory application and a 360° video. The recorded workload and vestibular responses likely stem from these specific content characteristics. Subsequent research should test standardized or calmer media to isolate modality effects from content-driven triggers. Finally, inconsistent localization introduced a potential variable regarding cognitive workload. While the study was conducted in Polish, the hand-tracking modality and the 360° video featured segments with English-only audio and instructions. This linguistic friction may have inflated NASA-TLX Mental Demand scores, and future evaluations must utilize fully localized content to ensure workload measurements strictly reflect interaction difficulty.

Ultimately, the results indicate that while contemporary VR offers meaningful opportunities for inclusion, current interaction modalities and hardware designs often fail to support users with diverse functional limitations. Controller-based interaction and passive 360° viewing demonstrated higher usability and lower subjective workload than hand-tracking, which introduced substantial friction due to system latency and a lack of haptic confirmation. Hardware ergonomics also presented significant barriers, as standard headsets caused physical discomfort for female participants and neck strain for wheelchair

users. Additionally, rigid spatial layouts and sudden camera translations triggered vestibular conflicts and safety concerns for participants with mobility impairments, while excessive sensory stimuli overwhelmed neurodivergent users. The accessibility of immersive environments depends heavily on implementing flexible input modalities, adaptable spatial layouts, and regulated sensory and camera dynamics.

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Developing a Prioritised Accessibility Guideline Checklist for XR Applications for Blind and Low-Vision Users

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Abstract

Aim: The use of Extended Reality (XR) apps is common in education, training, and entertainment, but there is limited focus on making them accessible to low-vision and blind users. However, several accessibility guidelines from different sources are not prioritised, making it hard for novice developers and students to use. In this paper, we introduced a single, prioritised checklist of XR accessibility guidelines for blind and low-vision users, based on a review of existing guidelines and expert rankings.

Methodology: We collected XR accessibility guidelines for low-vision and blind users from 6 primary accessibility sources. We then provided these guidelines to the 5 experts to rank them for accessibility for people with low vision and for people who are blind. Then, we used the Borda count method to rank them. The guidelines were grouped into three priority levels (A, AA, AAA) and aligned with the Perceivable, Operable, Understandable, and Robust (POUR) principles.

Results: We have developed a final checklist for the students. We tested the checklist in an educational setting, and it helped students understand and apply accessibility principles to their XR projects for people with low vision and blindness. Our results show that a clear, prioritised checklist can enhance the inclusivity of XR apps in educational settings.

Introduction

Digital accessibility challenges for low-vision and blind users are introduced by XR technologies, including virtual and mixed reality. Different types of XR applications rely heavily on complex interactions, visual cues, and spatial layouts, which can create accessibility barriers if these factors are not considered during planning. Although different platforms have their own accessibility guidelines, these resources are often scattered and not clearly prioritised, creating challenges for novice developers and students seeking to build accessible XR applications.

State of the art

Digital accessibility is no longer just a technical feature; it is a fundamental right that ensures equal participation in a digital-first society. For XR technologies to be inclusive, accessibility must be a proactive design requirement rather than a secondary consideration.

According to Verma et al., prioritizing accessibility is crucial for:

1. Bridging the Digital Divide: Providing structured access to information for those with sensory and intellectual disabilities (7,13).
2. Economic Empowerment: Enabling vocational training and employability for blind and partially sighted individuals through projects (8, 9, 10, 11).
3. Multimodal Autonomy: Replacing visual-only cues with haptic and auditory interactions to allow users to navigate complex 3D environments (12).
4. Unified Education**:** Standardising accessibility training (as seen in ENTELIS+) to help developers move past scattered, non-prioritized guidelines (9, 13, 15).

We have conducted a literature review to find established XR accessibility guidelines. The following XR guidelines were selected:

1. Meta Quest Virtual Reality Check (VRC) Guidelines (1)
2. Xbox Accessibility Guidelines (XAG) (2)
3. XRA Association Developer Guide (3)
4. Schell Accessibility Guidelines (4)
5. XR Accessibility User Requirements (W3C) (5)
6. Apple Vision Pro Accessibility Guidelines for Blind and Low-Vision Users (6)

We have selected the guidelines that are relevant to blind and low-vision users from these guidelines.

Table 1: This table now reflects the guidelines in order of importance, ensuring that all points are covered without repetition.

	Guideline	Description	Source
1	Legible Text and Controls	Ensures that text and controls are clearly legible, which helps users with low vision.	Meta Quest VRC, Xbox XAG
2	Screen Reader Compatibility	Ensures that XR applications are compatible with screen readers to provide audio descriptions of visual content.	W3C XAUR
3	Multi Modality	Uses a combination of visual, audio, and haptic feedback to provide clarity and direction.	Meta Quest VRC
4	Display Settings	Allows users to adjust display settings such as brightness and contrast to meet their visual needs.	Meta Quest VRC, Apple Vision Pro
5	Text-to-Speech	Essential for reading text aloud.	XRA Association, Apple Vision Pro
6	Audio Descriptions	Provides audio descriptions for visual content to assist players with visual impairments.	Xbox XAG, Apple Vision Pro
7	Simplifying Backgrounds	Simplifying backgrounds and reducing audio clutter can help users focus on essential elements without distraction.	XRA Association
8	Undo/Redo Functions	Providing undo and redo options allows users to correct mistakes easily.	XRA Association
9	Adjustable Speed	Allowing users to control the speed of interactions and set up action sequences.	XRA Association
10	Bypass Functions	Enabling users to bypass certain steps or sections can help them navigate more efficiently.	XRA Association
11	Save Progress	Allowing users to save their progress ensures they can return to their last point without losing their place.	XRA Association
12	Magnification	Users should be able to magnify or reduce objects and text.	XRA Association, Apple Vision Pro
13	Contrast and Edge Enhancements	Highlighting objects and text.	XRA Association

14	Peripheral Maps	Showing objects outside the field of vision.	XRA Association
15	Color Blindness Options	Provides options or techniques to distinguish colors, which is important for users with color vision deficiencies.	Meta Quest VRC, XRA Association, Schnell Accessibility
16	Shapes and Symbols	Providing additional visual cues.	XRA Association
17	Textures	Using textures to distinguish elements.	XRA Association
18	Translucent Layers	Making text more readable against backgrounds without obscuring important visual information.	XRA Association
19	Sensory Overload	Ensuring that visual and sound effects are enjoyable and not overwhelming.	Schell Accessibility
20	Menu Access	Ensuring menus are easily accessible and readable.	Schell Accessibility
21	Subtitles/Closed Captions	Providing subtitles or captions that can be read by screen readers.	Schell Accessibility
22	Inclusive Representation	Ensuring that the game includes diverse representation and avoids stereotypes.	Schell Accessibility
23	Accessibility Shortcut	Add, organize, and customize shortcuts for the tools and settings you use most.	Apple Vision Pro

Expert Ranking and Analysis Method

To prioritise these guidelines, five experts with experience in XR, digital accessibility, and HCI (Human-Computer Interaction) were consulted to rank them by their accessibility importance for low-vision and blind users.

Table 2: Borda Count Calculation for Each Guideline

Rank	Guideline	Expert 1 Rank	Expert 1 Points	Expert 2 Rank	Expert 2 Points	Expert 3 Rank	Expert 3 Points	Expert 4 Rank	Expert 4 Points	Expert 5 Rank	Expert 5 Points	Total Borda Count Score
1	03 - Multi-modality	1st	10	1st	10	1st	10	2nd	9	9th	2	41
2	12 - Magnification	2nd	9	4th	7	3rd	8	-	0	1st	10	34
3	02 - Screen Reader Compatibility	3rd	8	-	0	2nd	9	-	0	3rd	8	25
4	06 - Audio Descriptions	4th	7	3rd	8	-	0	-	0	4th	7	22
5	23 - Accessibility Shortcuts	5th	6	9th	2	-	0	1st	10	-	0	18
6	05 - Text-to-Speech	3rd	8	-	0	-	0	-	0	2nd	9	17
7	19 - Avoid Sensory Overload	7th	4	-	0	4th	7	6th	5	-	0	16
8	16 - Shapes and Symbols	6th	5	6th	5	10th	1	-	0	-	-	11
8	21 - Subtitles/Closed Captions	3rd	8	-	0	-	0	-	0	8th	3	11
9	13 - Contrast and Edge Enhancements	9th	2			7th	4	-	0	7th	4	10
9	20 - Menu Access	-	0	5th	6	-	0	7th	4	-	0	10
10	14 - Peripheral Maps	-	0	-	0	8th	2	4th	7	-	0	9
10	08 - Legible Text and Controls	-	0	8th	3	-	0	-	0	5th	6	9
11	18 - Translucent Layers	-	0	-	0	-	0	5th	6	-	0	6
12	15 - Colour Blindness Options	9th	2	-	0	9th	2	-	0	10th	1	5
13	09 - Adjustable Speed	8th	3	-	0	-	0	-	0	-	0	3
13	22 - Inclusive Representation	-	0	-	0	-	0	8th	3	-	0	3
14	17 - Textures	9th	2	-	0	-	0	-	0	-	0	2
	10 - Bypass Functions	11th	0	-	0	-	0	-	0	-	0	0
15	08 – Undo-Redo function			10th	1							1

Then, rankings were done by experts and analysed by the Borda count method. The Borda count method is a rank aggregation technique that assigns higher scores to higher-ranking items. Based on these Borda scores, the guidelines were grouped into three categories:

- A (Most Important): Essential for Accessibility
- AA (Important): Strongly recommended
- AAA (Not mandatory): Optional or Context Dependent

Classification using Accessibility Principles

There is a need to align the checklist with the established accessibility framework; we mapped it to the POUR principles: Perceivable, Operable, Understandable, and Robust. This classification provides developers with greater clarity, enabling the development of accessible XR apps across different layers of application development.

Result and Educational Evaluation

The accessibility guidelines are introduced to university students developing XR applications for low-vision and blind users as part of their coursework. Students are using these accessibility guidelines as a reference for developing XR applications. The feedback showed that structured and prioritized guidelines helped students better understand digital accessibility requirements and apply them more confidently. Students and their teachers value the prioritisation of guidelines, which helps them further focus on essential features under limited resource constraints.

Table 3: Prioritized Accessibility Guideline Checklist for XR Applications for Blind and Low-Vision Users

Category	Guideline	Description	Supports Blind Users?	Supports Low Vision Users?
1. Perceivable				
Multi-Sensory Accessibility	Multi-modality (A)	Provides visual, auditory, and tactile feedback.	✓	✓
	Screen Reader Compatibility (A)	Ensures XR interfaces work with screen readers.	✓	✗
	Text-to-Speech (AA)	Converts on-screen text into speech.	✓	✗
	Audio Descriptions (A)	Provides spoken explanations of visual content.	✓	✗
Visual Customization	Display Settings (A)	Allows customization of brightness, contrast, colors.	✗	✓
	Magnification (A)	Enables zooming in on text and UI elements.	✗	✓
	Contrast and Edge Enhancements (AA)	Improves visibility of objects and text.	✗	✓
	Colour Blindness Options (AAA)	Adapts color schemes for color blindness.	✗	✓

	Simplifying Backgrounds (A)	Reduces visual clutter for better focus.	✗	✓
2. Operable				
Tactile and Spatial Awareness	Shapes and Symbols (AA)	Uses distinct shapes/icons instead of relying on color.	✓	✓
	Textures (AAA)	Uses haptic feedback or textures for differentiation.	✓	✗
	Peripheral Maps (AA)	Provides accessible spatial maps for navigation.	✓	✓
Navigability & Interaction	Menu Access (AA)	Ensures menus are easy to locate and navigate.	✓	✓
	Accessibility Shortcuts (A)	Provides quick access to key accessibility features.	✓	✓
	Adjustable Speed (AAA)	Allows control over animation and interaction speed.	✗	✓
	Legible Text and Controls (AA)	Ensures text and interactive elements are clear.	✗	✓
3. Understandable				
	Undo-Redo Function (AAA)	Enables users to reverse actions easily.	✓	✓
4. Robust				
Inclusive Representation & Communication	Subtitles/Closed Captions (AA)	Provides captions for audio content.	✓	✓
	Inclusive Representation (AAA)	Ensures avatars and interactions reflect accessibility needs.	✓	✓

Future Scope

This research work presents a prioritised education-oriented XR accessibility guideline checklist for blind and low-vision users. We would like to include additional disabilities, such as mobility, cognitive, and hearing impairments, in the future to help students and novice programmers build inclusive XR apps from the planning phase.

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A Comparison of Four Braille Formats for Mathematics

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Abstract

Mathematical notation includes two-dimensional constructs such as fractions and superscripts, but braille is a one-dimensional code, so expressions must be linearized in a way that is compatible with the surrounding braille. Many mathematical braille codes exist, yet there is little data on how efficiently they encode the mathematics actually found in textbooks. We analyze roughly 600,000 expressions from 66 U.S. high-school and college textbooks, and compare four linear encodings of mathematics in braille: Nemeth, UEB, LaTeX, and ASCIIMath. 8-dot ASCIIMath produces the most compact output, followed by Nemeth 6-dot; LaTeX requires the most cells. We also report a detailed frequency breakdown of expression types, providing a data-driven basis for refining existing mathematical braille codes and for designing new ones.

Introduction and Background

When Louis Braille created his system in the 19th century, it only supported basic arithmetic. Systematic approaches to representing mathematics in braille emerged only in the late 20th century, and many of these codes continue to be refined. Supporting mathematics in braille is challenging for three main reasons:

1. early braille systems required two cells to represent digits (a number indicator before the letters "a–j")
2. mathematics uses hundreds of symbols (thousands in advanced topics); and
3. mathematical notation is inherently two dimensional and must be linearized;

While traditional embossed braille typically utilizes 6-dot cells, refreshable braille displays support an 8-dot format. These two additional dots are frequently used to indicate cursor position or text selection; 8-dot braille codes such as computer braille and EuroBraille can leverage the extra dots to represent all ASCII characters within a single cell. In contrast, 6-dot braille requires multiple cells for capital letters and many non-alphanumeric characters, such as backslashes or brackets. This single-cell efficiency makes mathematical typesetting languages like LaTeX and ASCIIMath intriguing options for braille math representation. This transition is already being made in some schools across Germany and Austria, where these formats are replacing the Marburg braille code.

The adoption of 8-dot braille reduces overall cell count and lowers cognitive load by eliminating the need for specific number, letter, or capitalization modes. We could not find papers with user studies that compared 6-dot and 8-dot braille for mathematics. However, research by Argyropoulos et al. [1, 2] found that 8-dot braille improved a reader's ability to identify stylistic changes like bold and italics despite it not being familiar. LAMBDA [3] serves as an example of a specialized refreshable 8-dot braille code designed specifically for mathematical content.

There are two significant downsides to 8-dot braille: unfamiliarity and size. The extra dots can result in vertical movement to read all the dots and/or fatigue due to flattening the finger to cover all the dots. Concave dots on refreshable displays can mitigate this problem, but that solution isn't available for embossed braille. 8-dot braille is rarely used for embossed braille due to the ~25% increase in size required for a line of text due to the extra row of dots.

Mathematical Braille Code Differences

Over 20 mathematical braille codes exist worldwide [4], each employing distinct strategies to address representational challenges. Larson [5] surveys these systems, while Van Leendert et al. [6] analyze regional variations using educator feedback from 16 countries. Their work illustrates how fundamental notations such as fractions and powers are encoded differently. The following discussion evaluates how various codes represent both simple and complex mathematical structures.

Numbers

1. Literary braille typically uses a number sign indicator to indicate that the letters 'a' – 'j' represent the digits 1, 2…, 9, 0. Many codes use this for mathematics also because it is familiar. For example, 123 is represented as ⠼⠁⠃⠉, where ⠼ is the number sign indicator. Number mode continues as long as one of 'a' – 'j' occurs, or a digit or decimal separator occurs, or a simple fraction line occurs.
2. The French math code uses Antoine numbers – 'a' – 'i' with the addition of dot 6. For example, 123 is represented as ⠠⠂⠆. The digit '0' is a special case and uses a different pattern ⠴. If the number is at the start of an expression, a cell with just dot6 (⠠) indicates it is a number.
3. Some codes use drop numbers – the letters shifted down one row. In Nemeth code, 123 is represented as ⠂⠆⠒. In a few cases, such as the start of an expression, a number indicator (⠼) is needed.
4. Whereas Nemeth always uses drop numbers, some codes such as Spanish/Portuguese Codigo Matematico Unificado (CMU), Polish, and Vietnamese codes use them for the denominator of numeric fractions. This special case shortens the code because none of the normal fraction indicators are needed. As an example, ¾ is represented as ⠒⠲ – no fraction indicator is needed before the drop number 4 used for the denominator. Polish braille also uses dropped numbers for subscripts.
5. 8-dot codes use a single braille cell that uniquely represents a digit. Various countries have different ways of representing digits with some using the same patterns as Nemeth or Antoine. Some add dot 8 to the normal 6-dot representation.

Mathematical Characters

Most braille codes require two or more characters to represent mathematical symbols, even for common ones such as "+" and "=". Particularly for Nemeth code, the braille representation often has some resemblance to print notation. For example, Nemeth for <, =, > is ⠐⠣ ⠶ ⠐⠜. In UEB, there is less resemblance to print notation: ⠈⠣ ⠸⠅ ⠈⠜. Most codes try to maintain some symmetry. For example, square brackets are represented as ⠷⠾ and ⠨⠷⠨⠾ in Nemeth, CMU, and Swedish braille and as ⠈⠣⠈⠜ and ⠸⠣⠸⠜ in UEB. For less common symbols such as "proper subset" (⊆), several braille cells are needed. Nemeth uses ⠸⠐⠣⠶ and CMU uses ⠈⠣⠶.

8-dot braille typically maps all of the keyboard characters to a single braille cell, but most mathematical symbols such as ⊆ require multiple braille cells. LaTeX uses mnemonic names such as \alpha (α), \times (×), and \leq (≤). ASCIIMath avoids using a "\" and often puts symbols together (alpha, xx, <=).

Linearizing 2-Dimensional Notations

There are two common ways to represent structure: start/end indicators for individual notations and a single structure indicator together with generic grouping indicators when the first or second operand is more than one character. Nemeth uses different start/end characters for each notation whereas most other codes use generic grouping indicators (similar to parenthesis). Polish braille has a mode

where grouping is implicit because spaces are replaced with dot-4 (˙) indicating all surrounding cells are grouped.

Table shows examples of a fraction, root, and superscript with both single character and multi-character operands. Structure indicators are shown in yellow and grouping indicators are shown in blue. It is immediately clear from looking at the table that indicators use a significant percentage of the representation for each notation so optimizations can reduce the indicator-to-content ratio.

Nemeth code only uses structure indicators. They are unique for each structure. In the fraction example, the indicators mark the start, middle, and end of the fraction: ⠹…⠌…⠼. The reader knows they are reading a fraction as soon as the start fraction indicator is encountered. In contrast, CMU groups non-simple operands with ⠰…⠰. The reader needs to learn fewer symbols but doesn't know they are reading a fraction until encountering ⠸ (/). UEB uses grouping operators for scripts and structure indicators for fractions and roots.

ASCIIMath is similar to CMU in that the reader doesn't know it is a fraction until "/" is encountered. LaTeX marks fractions and other structures before the operands, but is also heavily dependent on using braces to group operands as opposed to using specific syntax for each structure.[1]

Braille uses up a lot of space. Because of this, contracted (grade 2) braille was introduced which shortens common patterns. Like literary braille, mathematical braille codes have special cases. Most codes include dedicated rules for common notations such as numeric fractions and specific characters in the superscript (e.g., x',x°) and accents (e.g., $\hat{x}$, $\vec{x}$). For these cases, the superscript indicator is omitted saving a character. LaTeX and ASCIIMath only special case prime (') superscripts. These differences affect the complexity of the braille code and its compactness (efficiency).

Spacing conventions also vary: many codes introduce spaces to improve readability, even at the cost of additional cells, and some recommend adding extra spacing for early learners.

Table 1: Braille for 2D notations (yellow is structure indicator, blue is grouping indicator)

	Fraction: $\frac{2x}{3}$	Root: $\sqrt[n+1]{2x}$	Superscript x^{2^n+1}
Nemeth	⠹⠶⠼⠶	⠩⠜⠩⠶⠜⠩⠶	⠶⠶⠩⠶⠶⠩⠶⠩⠶
UEB	⠶⠶⠩⠶⠼⠶	⠶⠶⠩⠶⠩⠶⠶⠩⠶⠶⠩⠶	⠶⠶⠩⠶⠩⠶⠩⠶⠶⠩⠶⠩⠶
CMU	⠰⠩⠶⠶⠩⠶⠼⠶	⠹⠜⠩⠶⠜⠰⠩⠶⠶⠩⠶	⠶⠰⠩⠶⠩⠶⠰⠩⠶⠜⠩⠶⠩⠶
ASCIIMath	(2x)/3	root(n+1)(2x)	x^(2^n+1)
LaTeX	\frac{2x}{3}	\sqrt[n+1]{2x}	x^(2^n+1)

Study

While a user study would ideally quantify the cognitive load of proficient readers, recruiting a sufficiently large cohort is challenging; for instance, recent work by van Leendert et al. (2023) [7] included only three participants. Identifying readers who are proficient in multiple codes — particularly codes that differ in their use of structural versus grouping indicators — is often infeasible. We therefore adopt a corpus-based methodology, analyzing the frequency of mathematical patterns and their effect on the compactness of the resulting braille, in order to inform future revisions of mathematical braille codes.

To our knowledge, this is the first analysis of braille codes grounded in representative textbook usage. Our corpus comprises 595,000 expressions: 242,000 from 20 U.S. high-school textbooks and 353,000 from 46 college-level texts, with approximately 40% of the expressions in each book being duplicates.

[1] In LaTeX, square brackets ([…]) are used for optional arguments; required arguments use braces ({…}).

We excluded 31,000 tabular expressions (e.g., matrices and multi-step solutions), because MathCAT [8] is designed to produce single-line output for braille displays and no established single-line braille standard exists for such structures. Using MathCAT, we generated four representations: Nemeth and UEB, selected as widely used standards with fundamentally different design philosophies, together with LaTeX and ASCIIMath, which are common textual math formats that have been adopted as braille encodings in some regions. For the latter two, we also evaluated 6-dot versions produced via Grade 1 UEB ASCII character mappings to assess compactness for readers unfamiliar with 8-dot braille.

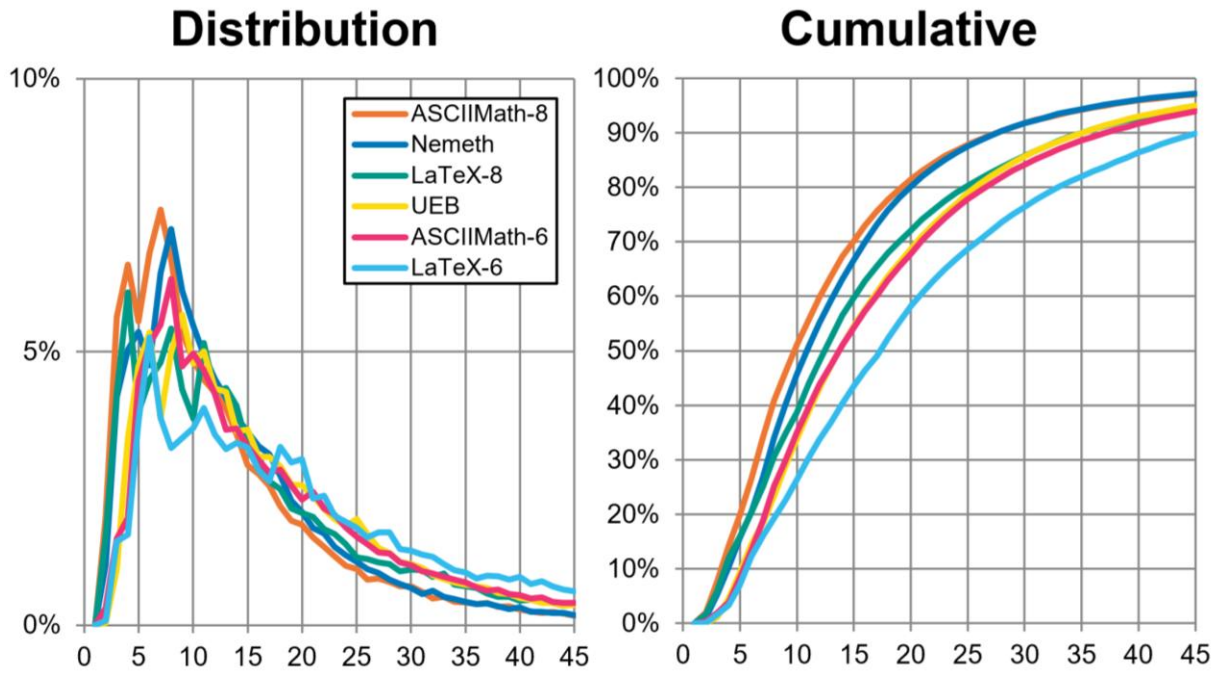


Figure 1: Distribution and Cumulative Occurrences braille cells of non-simple expressions (by code)

Results

Analysis of high school and college datasets revealed only a 1–2% variance in cell counts; subsequent results refer to the combined corpus. A significant 39% of the data consists of *simple* expressions (e.g., single variables or numbers).[2] To prioritize meaningful structures, the following analysis excludes these cases unless otherwise noted.

Figure 1 illustrates the distribution of cell usage across codes. The frequency graph shows a primary concentration between 4 and 12 cells. The cumulative distribution highlights that 8-dot AsciiMath and Nemeth are the most compact, while 6-dot LaTeX is the least compact. Notably, 50% of expressions fit within 10 cells using 8-dot AsciiMath, compared to 14 cells for UEB and 17 for 6-dot LaTeX. 6-dot AsciiMath performance aligns closely with UEB.

Table 2 evaluates code efficiency relative to standard braille display lengths (20, 32, 40, and 80 cells). On 20-cell displays, there is a 9% difference between AsciiMath and 6-dot LaTeX in terms of expressions displayable without panning; most expressions fit within 40 cells across all codes. These figures exclude potential delimiters required to signal the start or end of math mode.

Table 2: % expressions fit in common braille display widths

Code / # Cells	**14**	**18**	**20**	**32**	**40**
ASCIIMath	**67**	**78**	**81**	**93**	**96**

[2] For typographic consistency, sentence-level punctuation is often included within mathematical expressions. Expressions that were otherwise simple remained categorized as such despite these trailing characters.

Nemeth	63	76	80	**93**	**96**
LaTeX	56	68	72	88	93
UEB	51	64	69	88	93
ASCIIMath-6	51	63	68	86	92
LaTeX-6	40	52	58	79	86

Number efficiency is an important consideration in 6-dot braille: 73% of expressions contain numbers, with an average of 2.5 numbers per number-containing expression. For expressions that also include 2D structures, these figures rise to 81% and 2.9. In our generated UEB, nearly every number required a number indicator. Nemeth's use of dropped numbers accounts for over 50% of its efficiency gain relative to UEB.

Beyond purely linear notation, 2D expressions (excluding tabular data) account for 57% of the corpus and are where the linearization strategies of the codes diverge most. As shown in Table 3, superscripts, fractions, and subscripts dominate this category; all other 2D constructs together account for only 13% of expressions. We specifically investigate optimizations for simple child elements (**bolded** in Table 3), where codes that use bracketing indicators can omit those indicators, saving two cells per occurrence.

A further breakdown of superscripts shows that 41% are the digit 2 and 8% are the digit 3. Operator superscripts account for 14%; of these, primes represent 48%, degree symbols 28%, and asterisks 10%. Other operators each exceeding 1% include +, ⊥, and −.

Table 3: 2D MathML element child data (child is simple, integer)

2D Tag	% Lines	Mean per line	%2D Lines	% All 2D Tags	Mean per Line	All %		Child 1 %		Child 2 %	
						Simp	Int	Simp	Int	Simp	Int
msup	28	0.42	48	39	0.72	76	4	88	12	**86**	**61**
mfrac	18	0.25	32	24	0.44	**50**	**34**	**64**	48	**64**	52
msub	15	0.24	26	24	0.44	89	0	97	0	**92**	**59**

Discussion

Using the frequency data from Table 3, we can calculate the average indicator overhead per notation (Table 4). We assume a baseline of one cell per structural indicator—for example, one cell each for start and end markers.[3] Bracketing systems can omit end indicators for "simple" child elements, but they otherwise require two cells. The average indicator count (c_{avg}) for bracketing is calculated as:

$$c_{\text{avg}} = 1c_{\text{struct}} + 2\, c_{\text{bracket}} \times (1 - \%\text{simple})$$

As an example, superscripts appear in 28% of expressions, with 86% classified as simple. Consequently, most bracketing-based notations require only a single prefix indicator, but 14% of the time they need 3 indicators. From the formula we see that 1.28 indicators are needed compared to 2.0 for rigid structural systems. Column 5 and 6 in Table 4 further quantify the mean savings per 2D line (s_{avg}):

$$s_{\text{avg}} = \text{mean}_{\text{(2D) line}} \times (c_{\text{struct}} - c_{\text{avg}})$$

[3] This not true in many cases: LaTeX (e.g. "\frac") and ASCIIMath (e.g., "sqrt"). Swedish and a few other codes use 2 cells for the start and end. UEB uses 2 cells for the division line. Nemeth uses more for nested fractions.

Table 4: Saving per notation special case

Notation	special case	# cells: structure	c_{avg} : bracketing	Savings per line	Savings per 2D	Used by example(s)
Superscript: simple	86%	2	1.28	0.30	0.52	CMU, UEB
Superscript: integer	61%	2	1.39	0.26	0.44	Marburg (drop number avoids need for number indicator).
Superscript: 2 (one '2' indicator)	41%	2	1.00	0.17	0.30	Older codes: Taylor, 1971 Version of French braille
Superscript: operator	14%	2	0.00	0.12	0.20	Most codes
Fractions: simple	64%, 64%	3	1.72	0.32	0.52	CMU
Fractions: both numeric	34%	3	0.00	0.24	0.45	Polish (uses drop numbers for denom and skips "/" between num and denom)
Subscripts: simple	92%	2	1.16	0.28	0.37	CMU, UEB
Subscripts: numbers (no indicators)	59%	2	0.00	0.28	0.52	Nemeth

The optimizations in Table 4 reduce complexity by 3 cells per expression. However, such optimizations may increase cognitive burden or syntactic ambiguity. In Nemeth, for instance, the omission of an end indicator for numeric subscripts necessitates an additional rule to handle subsequent digits.

Cell counts for LaTeX and ASCIIMath were generated via MathCAT using the German technical specification [9]. This standard prioritizes clarity by inserting spaces and occasionally specifying parentheses around arguments (e.g., "root(x)" instead of the technically legal "root x"). Because radical expressions are relatively infrequent in the corpus, these additional grouping symbols do not significantly impact overall code length. Conversely, the impact of spacing is substantial: for 8-dot AsciiMath, 50% of expressions fit within 9 cells without spaces compared to 10 cells with recommended spacing; for LaTeX, this disparity increases to 11 cells versus 13.

Nemeth code employs repeated indicators for nested fractions and radicals to clarify the structural hierarchy of complex expressions. While this design significantly increases the cell count for nested notations, Table 5 demonstrates that such occurrences are relatively rare (e.g., 3% of the fractions have a fraction inside). Consequently, the cognitive benefits provided by these structural markers likely outweigh the marginal increase in the overall cumulative cell count.

Table 5: % of nested 2D elements

Depth	**mfrac**	**msqrt**	**mroot**	**msub**	**msup**	**msubsup**	**munder**	**mover**	**munderover**
2	3.12	0.34	0.03	1.29	3.00	0.03	3.68	0.77	0.00
3	0.00	0.01	0.00	0.00	0.03	0.00	0.26	0.02	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00

Conclusions

While this study emphasizes code efficiency, compactness does not always correlate with increased reading rates or comprehension. A terse code may impose a significant cognitive load if it requires the

reader to internalize numerous complex rules. However, a system that achieves both simplicity and compactness is inherently superior to more verbose alternatives. ASCIIMath serves as a model for simplicity, yet it lacks the expressiveness required for sophisticated mathematical notations and lacks standard names for many specialized characters. Consequently, some ASCIIMath implementations fall back to LaTeX to represent complex structures and character names.

While this analysis did not evaluate specific character encodings, the textbook corpus enables future research into character frequency. Such data can inform the design of more compact character sets, provided the encodings preserve structural consistency. Essential design principles include:

1. **Symmetry** between paired delimiters (e.g., open and close brackets).
2. **Logical relationships** between standard and negated operators (e.g., = and ≠) through consistent modifiers.
3. **Structural similarity** between related symbols, such as long and short arrows.

Our findings provide a data-driven foundation for refining existing braille codes or designing new ones. The data suggest that targeted optimizations, such as Nemeth's special case for integer subscripts, yield measurable gains in compactness. More broadly, because most subexpressions are short/simple, codes that optimize for these structures in a uniform manner will achieve greater compactness without sacrificing simplicity.

Finally, while the German specifications for LaTeX and ASCIIMath advocate for spaces to improve readability, proficient users often omit these to prioritize efficiency. Because modern refreshable braille displays facilitate personalization, we envision a shift away from rigid, universal standards. Future systems should customize output based on user expertise: providing verbose, accessible versions for beginners and terse, space-efficient versions for experts. Assistive technology should ultimately adapt to the individual rather than forcing the user to adapt to a rigid standard.

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Appendix A

For reference, Table 6 is the complete 2D Structure table summarized in the paper. "mmultiscripts" is not common in the textbooks in this study, but would be more common in chemistry textbooks.

Table 6: 2D MathML element child data (child is simple, integer)

2D Tag	% Lines	% All 2D Tags	Mean per Line	All %		Child 1 %		Child 2 %		Child 3 %	
				Simp	Int	Simp	Int	Simp	Int	Simp	Int
msup	48	39	0.72	76	4	88	12	86	61	0	0
mfrac	32	24	0.44	50	34	64	48	64	52		
msub	26	24	0.44	89	0	97	0	92	59		
msqrt	7	5	0.10	65	52	65	52				
mover	4	3	0.06	74	0	75	3	99	0		
mroot	2	1	0.02	46	25	46	26	100	86		
msubsup	2	2	0.03	68	0	97	0	82	54	80	34
munder	1	1	0.02	14	0	90	2	19	0		
Munder-over	1	1	0.02	1	0	100	0	2	0	96	16
menclose	0	0	0.00	67	35	67	35				
Mmulti-scripts	0	0	0.00	0	0	92	1	57	37	7	2



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From Assistance to AI: Inclusion and Co-design in Later Life, Co-Creating Digital Inclusion for Older Adults in the Era of AI

Engaging Older Adults through Artefact-Driven Approaches for AI Literacy Development: A Multi-Stakeholder Model for Digital Inclusion

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Abstract

As Artificial Intelligence (AI) becomes deeply integrated into modern ICT and e-Accessibility services, older adults face a growing "digital divide" often characterised by a lack of awareness regarding how automated AI systems frequently functioning as "black boxes" infiltrate and impact their daily lives. This paper presents a multimodal workshop model designed to foster critical AI literacy among older adults, transitioning them from passive recipients to active stakeholders. Utilising an Action Research framework, the study details the co-creation phase of a three-phase national Age-Friendly AI literacy initiative in Ireland. Central to the methodology is the use of tangible exhibits as pedagogical tools. The 'AI Mask', a physical embodied conversational agent, is used to demystify AI concepts such as Large Language Models (LLMs), generative AI and machine learning through hands-on interaction. The 'Art or AI?' exhibit incorporates a public engagement activity where participants learn to distinguish between human-made and AI-generated art, fostering discussion on deepfakes and technological manipulation. Initial results from workshops involving over 250 older adults indicate significant improvements in self-reported understanding of and confidence in discussing AI. By prioritising physical accessibility, inclusive design and facilitated peer-to-peer discussions, the study demonstrates that artefact-driven approaches can effectively lower cognitive barriers and enable older populations to critically evaluate the societal and ethical implications of AI thus increasing confidence and AI literacy skills.

Introduction

As AI technologies continue to evolve at an accelerated pace and become the backbone of modern ICT and e-Accessibility services, their impact is felt across virtually every sector, reshaping how we interact with services, information, and with each other [1]. While AI promises advancements in various domains, it also necessitates a critical examination of digital inclusion, particularly for demographic groups that may be disproportionately affected by rapid technological changes. Older adults, a growing segment of the European population [2], stand at a unique intersection of potential benefit and potential marginalisation in this AI-driven era [3]. The traditional "digital divide" has evolved; for older adults, the barrier is no longer just a lack of hardware access or digital skills, but often a lack of awareness of how automated AI systems frequently functioning as "black boxes" which impact their privacy, healthcare provision, civic participation and their ability to navigate essential online services such as government and financial platforms [4]. This can lead to feelings of anxiety and a subsequent reluctance to engage with essential digital services. Fostering public confidence and critical engagement with AI is essential to ensure that the development and deployment of AI align with societal values and addresses public concerns for all.

This paper explores how tangible exhibits are incorporated in a multimodal workshop as a mechanism to build competence and confidence for older adults to engage with AI. Rather than promoting AI adoption, these facilitated workshops foster critical AI literacy and are designed to shift older adults from passive recipients of AI to active stakeholders in the AI landscape. The qualitative insights and

data gathered through these hands-on interactions with the exhibits form an important part of the output of the co-creation phase of a national Age-Friendly AI literacy training initiative designed with and for older adults and will feed into the subsequent dialogue phase of this three-phase (co-creation, dialogue and training development & rollout) project. Ultimately the final stage of the project, will involve the development and national rollout of a tailored Age-Friendly AI literacy content, reflecting the findings from both the co-creation and dialogue phases.

Background

Numerous initiatives globally have focused on enhancing digital literacy among older adults [5, 6] recognising its importance for social inclusion and for access to essential services. These efforts often share common themes, including the provision of accessible content and interfaces [7] community-based learning environments and tailored training programs [5]. In Ireland, organisations like Age Action have implemented programs such as 'Getting Started' [8] which provides foundational digital skills to older people nationwide, demonstrating the efficacy of localised, supportive interventions. Similarly, in the United States, initiatives like Senior Planet [9] offer a learning community for older adults, focusing on technology education to enable them in various aspects of life, from financial management to social connection. These programs underscore the importance of practical, hands-on learning experiences that directly address the needs and anxieties of older adults.

Efforts to improve inclusion, such as listening to people's views, co-designing tailored and accessible training programs [10] and age-friendly digital interfaces, with safeguards for respecting users' privacy and security [4], are key strategies to enable older citizens to confidently and independently engage with digital tools in this AI driven digital age.

Qualitative studies reveal common concerns among older adults regarding technology adoption, including issues of privacy, data security and the fear of being scammed or phished [11]. There is also a notable apprehension about AI potentially replacing human contact, particularly in sensitive areas like healthcare [12] and finance. These concerns highlight that digital literacy extends beyond mere technical skills; it also encompasses critical understanding, ethical considerations and the ability to navigate the societal implications of technology, as outlined in the Digital Competence Framework for Citizens, DigComp Framework [13]. Successful AI literacy interventions must not only teach technical skills but also foster a critical perspective on AI, addressing fears and building trust through transparency and open dialogue.

Our work integrates these lessons by moving away from traditional instructor designed and led training towards multimodal workshops that bring together older adults, community advocacy groups, academics, industry partners and policymakers to identify specific AI literacy needs with and for this demographic. By using exhibits like the 'AI Mask' and 'Art or AI?' the workshops provide an inviting, hands-on environment that transforms abstract technical concepts into tangible experiences. These artefacts serve as critical pedagogical tools to spark deeper, evidence-based conversations regarding the ethical and societal implications of AI and to gather insights that will inform the co-design and development of more in-depth discussion scenarios for the dialogue phase of a national AI literacy training project for older adults.

Methodology

This work employs an Action Research (AR) framework [14], focusing on an iterative cycle of action and reflection to address the AI divide. It is part of the co-creation phase of an Age-Friendly AI literacy training project and serves as the primary 'Action' stage of the research, where multimodal workshops function as a mechanism to engage older adults in conversations about AI. This phase moves away from traditional, top-down instruction toward an interactive model using tangible exhibits as catalysts for confidence building and engagement.

Engagement through Supported Artefact-Driven Interaction

To ensure the research is grounded in the lived experiences of older adults, this co-creation phase of the project utilises two core exhibits as pedagogical and data-gathering tools. These artefacts are designed to facilitate engagement and transform abstract "black box" technologies into physical, relatable experiences. This enables participants to move beyond theoretical fear to practical scrutiny and allows for the identification of specific anxieties and AI literacy gaps within the older adult demographic.

The 'AI Mask' exhibit presented in Figure 1, the technical design and detail of which is outlined in [15], is a physical embodied conversational agent [16] that provides an accessible, tangible and embedded interface to embody different types of AI including large language models (LLMs), generative AI, machine learning, natural language processing, and computer vision systems. To build confidence and encourage engagement, facilitators worked closely with participants, guiding them from creating basic prompts through to developing more nuanced ones. This allowed participants to experience speech-to-text and text-to-speech capabilities, witness how AI responds, and then specifically explore generative AI features such as AI's varying response accuracy, the presence of bias, and the phenomenon of AI hallucinations (where the AI produces convincing yet false information) overcoming fear of engaging with the technology to having the confidence to scrutinise and discuss its impacts. Sample prompts were provided to participants to aid in both initial engagement and to specifically elicit effects like hallucinations. The mask's face-tracking and jaw movement features made the interaction more human-like and engaging. This exhibit was used to showcase and provoke conversations about AI technologies as well as broader discussions on AI's role in creative processes, its ethical implications, and its effect on society in general.

The Art or AI?: exhibit, presented in Figure 2, is a public engagement activity developed by the Research Ireland ADAPT Centre for digital content technology [17], with embedded generative AI concepts and technology in its core design. It challenges participants to distinguish between images of human-made art and AI-generated art. 'Art or AI?' was developed to foster AI literacy by providing a tangible and interactive experience with AI-generated content where participants interact with a physical display to make their distinctions. Through facilitated discussions and an interactive digital quiz, the exhibit enables participants to develop a foundational understanding of the capabilities and limitations of generative AI including deepfakes and the potential for technological manipulation of reality. Participants scored an average of 7/10 in the digital quiz. While this average score demonstrates a degree of success when it comes to discerning between AI-generated images and human-created artworks, it also highlights the ongoing need for accessible educational initiatives that enhance AI literacy among the general public. The 'Art or AI?' exhibit and quiz can be accessed digitally at: https://bit.ly/ArtorAI.



Figure 1: Left, Exhibit "AI Mask2"

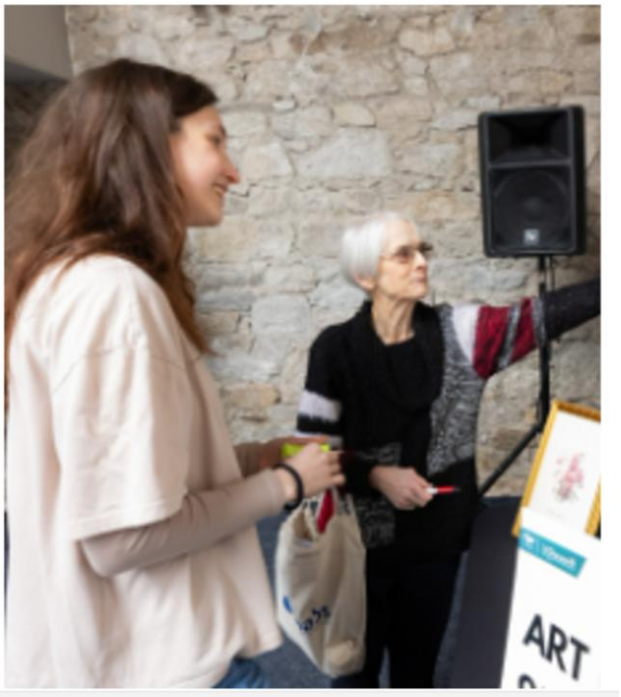


Figure 2: Right, Exhibit "Art of AI?"

Accessibility, Inclusion and Critical Literacy

Within this phase of the project the implementation of our workshops was specifically designed to address the unique constraints of older populations. Central to this approach is the clarification that the programme is not designed to promote AI adoption, but rather to foster critical AI literacy for this demographic. By focusing on critical agency, we address the challenges of engaging older adults in discussions about how these technologies impact their lives.

To ensure convenience and engagement we partnered with over twenty community groups, including Libraries Ireland, to host the workshops in trusted community settings that are both physically accessible and familiar to the participants. We actively promoted our workshops as requiring no prior knowledge of AI, facilitating group engagements that encourage participation across all levels of experience. To build foundational confidence, we began each session by outlining where AI is already embedded in everyday services, such as predictive texting, navigation apps, and recommender systems (e.g., Netflix), providing a relatable context for more complex discussions and interactions with the exhibits. We delivered all workshops in person to maintain a human-focused environment that avoids the isolation often associated with online training. Engagement with the physical artefacts is supported by trained facilitators and supplemented by tailored handwritten guides and posters to ensure the information remains approachable. To ensure technical limitations do not exclude any participant, we provided physical paper copies of all workshop materials and survey forms, deliberately avoiding online interaction tools like Mentimeter or the exclusive use of QR codes. We ensured all venues were wheelchair accessible and the exhibits were positioned at sitting level to accommodate wheelchair users, two of whom attended our workshops, and those who preferred to remain seated. Observational data indicated that providing seating at the exhibit stations facilitated longer, more meaningful, and more engaged interactions with the exhibits. We assigned dedicated companions to help blind and visually impaired participants, two of whom attended our workshops, with for example form filling (consent and survey forms) and engagement with the demos, ensuring they could fully engage with the sessions. These participants contributed unique and invaluable insights into their specific lived experiences with AI technologies. For participants who wore hearing aids and/or reported being hard of hearing, we used microphones for all presentations and group discussions. Following direct feedback

regarding background noise and visibility, we implemented closed captioning for presentations, ensuring that captions were positioned at the top of slides for better line-of-sight visibility and restricted number in later workshop sessions to suit venue sizes. By integrating these specific design considerations, we successfully established a robust mechanism for engaging older populations in conversations about AI.

From Action to Reflection

To ensure long-term impact and reflect the needs of the demographic, the 'Reflection' component of this AR cycle involves analysing the qualitative data gathered during the interactions with older adults at the multimodal workshops. Rather than assuming what older adults need to know, these workshops allow participants to identify their hopes, ideas and concerns about AI. These insights provide the evidence base to co-create discussion scenarios for the dialogue phase of the Age-Friendly AI literacy project.

Throughout the project activities we are bringing together older adults, service providers, advocacy group leaders, academics, industry partners and policymakers to facilitate stakeholder interaction and thus create a feedback loop where the opportunities and challenges of aging-in-place are directly shared by those influencing AI driven digital policies, technologies and services.

Initial Results

In the first six months of the project more than 250 older adults have participated in the mulitmodal co-creation workshops in five regional community settings throughout Ireland. The demographic data collected included age, gender, educational and digital skills level and the results of these are presented by Kelly et al. (2025) [18]. As also outlined in that paper and shown below in figures 3 and 4, a comparative analysis of pre- and post-event survey responses for a sample of 81 participants (this sample size was chosen because a change in the survey structure after two of the workshops had been completed was required to more closely align the pre and post survey questions) revealed significant improvements in participants' reported perception of their understanding of AI and confidence in sharing their views about AI.

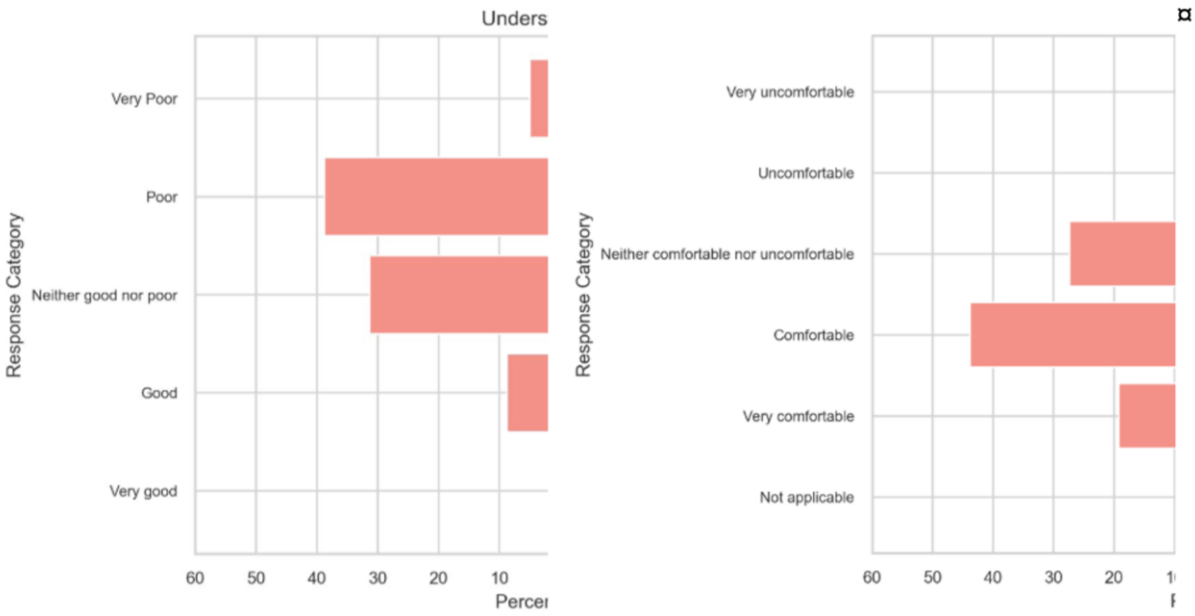


Figure 3: Left , Pre- & post-survey results of participants' self-reported understanding of AI
Figure 4: Right, Pre- & post-survey results of participants' self-reported confidence in speaking about AI.

Qualitative and quantitative data, gathered through multi-choice and open-ended survey questions and facilitator observations, provided rich insights into participants' experiences with the 'AI Mask' and 'Art or AI?' exhibits and are presented next.

'AI Mask' Impact

Direct quotes: (from a participant who had not used Generative AI before) "I'm surprised at how realistic the conversation is" 2. (from a participant who had used Generative AI previously) "this could be a useful companion for someone living alone" 3. "Where does the data of conversations [with the mask] come from and go to?"

Observations: Facilitators noted that the mask's animatronic features (moving eyes and jaw) enhanced engagement, fostering a sense of connection and reducing initial apprehension. The seamless interaction provided by the mask's embedded computing devices, sensors and actuators, along with its speech-to-text, text-to-speech and facial tracking functionalities, contributed to a natural and intuitive user experience.

Discussions provoked: The mask facilitated discussions around the nature of AI responses, the concept of AI hallucinations, and the potential for AI to mimic human interaction. Two facilitators in particular summed it up with their comments "it was very thought provoking for people, that was the sense I got from their reactions", and "participants reacted very well to the AI mask, they really got the idea of showing the different aspects of AI to people with lower digital skills. The interactions were 10 to 15 mins long which is really good interaction."

'Art or AI?' Impact

Direct quotes: "Really engaging, designed with the public in mind using clear presentations and easy-to-use technology. AI was presented as neutral rather than a threat." 2. "No AI background knowledge needed. It highlights the difficulty in detecting real and AI generated while encouraging people to trust their gut feeling if something feels "off"." 3. "Excellent".

Observations: The 'Art or AI?' artefact, an exhibit of physical artworks alongside an interactive digital quiz, served as a tangible artefact for direct engagement. Participants selected their answers via a digital

quiz interface, receiving instant, embedded feedback that not only introduced generative AI concepts, but also fostered embodied discussions about AI's impact on creativity and the Arts.

Discussions provoked: The exhibit was designed to provide a tangible encounter with AI to stimulate conversations about creativity, authenticity, the role of human artists in an increasingly AI-driven world and the ethical considerations of AI-generated content. Participant feedback highlights the effectiveness of 'Art or AI?' as an accessible and engaging public engagement tool for AI literacy. The perspectives shared highlight the exhibit's success in demystifying AI and fostering a balanced view of the technology. The immediate feedback on whether an artwork was human or AI-generated prompted deeper reflection, encouraging not just cognitive insight but also an intuitive, gut feeling about AI-generated content. The concise yet emphatic remark: "Excellent" further demonstrates the positive user experience and overall impact of the tangible, embodied and embedded 'Art or AI?' artefact in fostering an approachable and thought-provoking encounter with generative AI.

Conclusions and Future Work

The findings presented above collectively demonstrate that the multimodal workshops, incorporating interactions with tangible exhibits and facilitated discussions, are highly effective in enhancing AI literacy and fostering critical engagement with complex AI concepts among older adults. They not only improve knowledge and confidence but also enable participants to engage critically with AI, articulate their hopes and concerns thus contributing to a more inclusive dialogue about AI's societal implications.

The study highlights that the physical presence of the 'AI Mask' and the gamified nature of the 'Art or AI?' exhibit effectively lowered cognitive barriers and functioned as engaging objects that allowed participants to scrutinise the technology rather than just consume it. Participants moved from being intimidated by AI to gaining the confidence to critically evaluate its impact and articulate specific concerns rather than general apprehension. By making AI's benefits but also its limitations visible—particularly through intentional demonstrations such as showcasing how generative AI can exhibit hallucinations and bias—the workshop successfully fostered critical AI agency. This shift towards informed critique is a hallmark of literacy and is essential for meaningful civic engagement in an AI-driven world.

The Action Research model provides a scalable blueprint for addressing the digital divide in the age of AI. By treating older adults as active participants rather than subjects, the "Age-Friendly AI literacy" programme ensures that e-Inclusion efforts are grounded in real-world needs. This work proves that with the right multimodal tools and inclusive methodologies, older adults can move from being a "digitally excluded" group to being active, informed contributors to the future of AI policy and practice. The work underscores that the future of e-Accessibility lies not just in better technology, but in better conversations—ensuring that those most at risk of digital exclusion are included in the dialogue on technological advancement.

Findings from this phase will inform the co-creation of tailored scenarios that will be used during the dialogue phase of the project to further explore the main hopes and concerns of older adults that have surfaced during this co-creation phase. A participatory approach to the development of further engaging artefacts to support this next phase of the project, will address other complex AI concepts and cater for diverse learning preferences. This could include artifacts that explore the nuances of data privacy, algorithmic decision-making or recommender systems, further deepening the experiential learning aspect. Ultimately the outputs from both the co-creation and the dialogue phases will be used in the final phase of the project during which the Age-Friendly AI literacy training content for older adults will be developed and rolled out on a national scale through our community partnership network. By continuing to foster meaningful dialogue, providing accessible and engaging learning experiences, and advocating for inclusive AI development, this initiative aims to enable older adults to confidently participate in and benefit from an AI-driven future, ensuring that technological progress serves all segments of society equitably.

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Co-Creating Digital Inclusion for Older Adults in the Era of AI

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Abstract

Europe's demographic landscape is changing due to an aging population, and, therefore, new ways of engaging the elderly in research and technology need to be adopted. This paper describes the activities of COST Action CA22167, Participatory Approaches for Older Adults Companion (PAAR-net), here specifically with a focus on WG3: Technology and Innovation. We consider how a participatory paradigm can address digital inequalities and disrupt ageist assumptions in contemporary technology design, notably Artificial Intelligence (AI). Through the lens of a 2025 international workshop held in Lithuania, the research explores the dual nature of Generative AI as both an empowering tool for independence and a potential risk to the cognitive autonomy and critical thinking of older learners. By using seniors as "experts-by-experience", PAAR-net is advocating for an inclusive turn of social innovation to avoid the digital shift escalating previous patterns of social exclusion.

Keywords: Older Adults, Digital Gap, Codesign, Artificial Intelligence

Introduction

With increasing numbers of older people in Europe, ageing research and policy will need to be revised to accommodate this lived experience. Far too often the elderly, those over 65, are treated as passive recipients to be researched rather than valuable participants in innovation. In 2023, the PAAR-net COST Action was launched to take down these walls, and set up a pan-European network to embed the 65+ voice at every level of science [1].

The main goal of PAAR-net is to support more inclusive social innovation by listening to and learning from older adults, especially those who often feel excluded from society. Rather than treating older people as passive research subjects, PAAR-net sees them as active partners and experts of their own lives. In practice, this means inviting people aged 65 and over to take part in every stage of a process; from defining research questions to co-designing solutions, and contributing to policy recommendations. By doing this, PAAR-net challenges age stereotypes, values the rich life experience of older generations, and supports them in becoming agents of change in their own communities [2,3].

Its underlying purpose is to promote social justice and equity, including for marginalised groups (rural elders, migrants and low income seniors) often excluded from social discourse. In the larger context of the Action, Working Group 3 (WG3) focuses among others, on the "digital divide". This chasm is not just an equipment gap, but it tracked with low digital literacy, frustrating interface design and a wider tech culture that largely excludes the diverse needs of older adults.

This group investigates how to reduce digital inequalities among seniors who lack digital competence [4]. It explores barriers to technology use – for example, low digital literacy, usability and accessibility issues in device interfaces, or affordability of internet access – and works on innovative, user-driven solutions to overcome these barriers. WG3 also promotes digital literacy initiatives to empower older adults with the skills and confidence to use technology in their daily lives. Furthermore, the group advocates for equitable access to digital tools and infrastructure, recognizing that many older people in different settings (rural communities, care homes, low-income neighborhoods) need better support

to get online. The ultimate goal is to enable older generations to fully participate in the digital society, rather than being left on the wrong side of the "grey digital divide."

As Generative AI is increasingly used in important services, we must ensure that these systems are co-designed to be accessible, ethical and supportive of older adults' autonomy.

Methodology: The Co-Production Model

A core premise of PAAR-net is that involving older adults as equal partners in research – as experts-by-experience – will lead to more effective and empowering innovations.

Crucially, WG3's participatory research targets older adults who lack digital competence or confidence – those most at risk of exclusion in a digitalizing world. Many seniors in Europe still have low digital skills or no internet access; for instance, as recently as 2017, 44% of EU residents aged 65–74 had never used a computer [5], and in 2024 in the UK, around one-third of people over 65 could not perform basic online tasks while one in six did not use the internet at all [6]. These statistics underscore the urgency of WG3's mission to bridge the digital divide for older generations.

WG3 (Technology and Innovation) exemplifies this participatory methodology. WG3 adopts a co-production research approach in which older adults are integrally involved at every stage of the process, from needs analysis to intervention design to evaluation [4].

WG3 methodological approach is based on coproduction, an approach that treats older adults as equal partners rather than subjects to be researched. This approach explicitly opposes top-down technological "fixes", in preference for co-creative spaces, where seniors are enabled to express their desires and experiences.

Iterative Design Cycles: Heuristic evaluation takes place throughout the complete product design process from needs assessment to prototyping to final appraisal.

Tools of Engagement: Such hands-on devices as focus groups, and intergenerational codesign workshops are used by researchers [7].

Intergenerational Learning: By matching students from IT faculties or young researchers with older adults, project promotes mutual relation in which IT expertise comes hand in hand with the wisdom of life. This serves to break down stereotypes at both ends of the age spectrum.

Empowerment and Capacity Building: The approach is transformative; not only are seniors contributing to new research, they are also provided with digital literacy training so that they gain practical skills and confidence in using devices like tablets or voice assistants.

An example of this is the serious game that was designed to improve a user's memory, coordination and fine motor skills as the game was largely backed by the user-centred design. The design process also used participatory design [8]. Such methods have been shown to enhance the relevance and acceptance of innovations, as older users help ensure that new technologies address real needs and are accessible [9].

Results and Discussion: Navigating the AI Frontier

Research Findings and Analysis on AI

The first results based on WG3 show that "digital ageism" is still a barrier to inclusion. The designers usually think that older adults cannot learn so they use very small fonts and complex navigation and do not provide the option of human support.

The function of Generative AI

Artificial intelligence poses an interesting paradox for the aged. At one hand, smart homes with AI and personalized health reminders can strongly enhance independence and well-being. On another note, the fast-paced innovation of AI technology is often taking place without taking into account the preferences of older aged people. This could result in the development of automatic services that end up confusing or alienating the very people they are made for. Also, a worrying ethical concern of the results by using AI with bias and hallucinations.

Case Study

The Vilnius International Knowledge Exchange Event Case Study In April 2025, 80 stakeholders, including older co-creators, were instructed to address the issue during an international workshop in Vilnius, Lithuania. A "World Café" session focused on the accessibility of Generative AI [10].

Participants explored whether reliance on AI would damage your intelligence. Those who were older argued that their decision-making experience of 50 years served as an internal compass, leading them to use AI as one source of advice and not necessarily as an authority.

The slippery slope of convenience cognitive dependency could be e.g.:

- after having the GPS, users didn't bother to remember the route,
- if an AI answers every question, we might don't make the habit of asking ourselves.

AI should seek the user's attention and encourage them to review and modify its output, and the user must always remain mentally active when engaging with the AI.

During this workshop, participants had to answer an online survey with the following questions, working in small groups (3-4 people)

1. Do you have any ideas on how AI can help older adults overcome the digital divide and their lack of IT skills? How can AI help them in their everyday lives?

Summary the answers to the 1st question:

- AI helps older adults bridge the digital divide by offering voice-controlled, easy-to-use interfaces and personalized, step-by-step guidance.
- It supports learning by adapting to each person's pace, helping them navigate apps, websites, and devices confidently.
- In daily life, AI provides reminders for medication, appointments, and other tasks while also assisting with health monitoring and smart home control.
- Conversational AI tools and chatbots offer companionship, reduce loneliness, and make communication with family and friends easier.
- Overall, AI empowers older adults to live more independently, safely, and confidently in a digital world.

2. How do you think older adults' extensive life experiences shape their engagement and interaction with GenAI in learning situations?

Summary the answers to the 2nd question:

- Older adults' extensive life experiences shape how they engage with generative AI by allowing them to connect new information to what they already know and ask more thoughtful, context-rich questions.
- Their critical thinking and practical judgment help them evaluate AI outputs carefully and use them in meaningful, goal-oriented ways.

- Many approach GenAI with curiosity but also caution, valuing clear explanations and practical applications over abstract or experimental uses.
- However, some face challenges such as limited digital literacy, slower adaptation, or skepticism toward new technologies.
- Overall, their experience-driven, reflective learning style makes their interaction with GenAI more deliberate, purposeful, and focused on real-life relevance.

3. In what specific ways might older adults' educational background influence their critical thinking and learning behaviours when using GenAI?

Summary the answers to the 3rd question:

- Older adults' educational backgrounds strongly influence how they engage with generative AI, shaping their confidence, critical thinking, and ability to question or interpret AI outputs.
- Those with higher or more formal education tend to analyze AI responses more deeply, cross-check information, and use GenAI as a supportive tool rather than an authority. In contrast, adults with less formal education may rely more passively on AI, requiring clearer guidance, simpler interfaces, and practical examples to learn effectively.
- Their field of study also affects interaction—STEM backgrounds promote analytical questioning, while humanities backgrounds encourage reflective and interpretive use.
- Overall, education determines how older adults trust, adapt to, and learn from GenAI, influencing both their confidence and learning outcomes.

4. How might cognitive aging impact their critical appraisal of the information generated by AI? Can accumulated life experiences balance or offset cognitive changes?

Summary the answers to the 14th question:

- Cognitive aging can slow processing speed, memory, and attention, making it harder for older adults to critically evaluate AI-generated information.
- However, their accumulated life experiences and wisdom often compensate by improving judgment, pattern recognition, and skepticism.
- These experiences help them detect inconsistencies or biases in AI outputs, especially in familiar areas.
- Education and familiarity with technology also influence how effectively they engage with and question AI content.
- Overall, while cognitive decline may affect speed and depth of analysis, life experience fosters balanced, reflective, and context-aware critical thinking when interacting with generative AI.

The workshop concluded that AI needs to engage users in a way that gets them talking and encourages them to tweak outputs. This keeps minds active. People need to feel involved in the process, not just passive recipients of information.

Surveys after the event showed that discussions around advanced technologies like AI were empowering, especially for older adults. It helped clear up confusion about the tech, making it less intimidating and reducing that fear of the unknown.

Now, about digital fairness. WG3 is all about this idea that access to technology should be seen as a right, not just some nice thing for the privileged. It's crucial to create tools that can adapt to the changing needs of people, whether they're facing physical challenges or cognitive ones. The goal is to develop systems that uphold dignity and allow for autonomy. To really make this happen, the project is pushing for funding agencies and developers to focus on involving older adults right from the design stage.

The discussion suggested that speaking about novel technology like AI empowered seniors as it demystified the tech and removed fear of the unknown. Fostering Digital Justice WG3 advocates for digital fairness, where access to technology is a right and not a privilege. Creating tools that respond to changing physical or cognitive abilities; systems that offer dignity, support. To embed these values into agencies, funders and developers must be encouraged to finance projects involving older adults at the design stage.

At the end of the workshop, everyone had to fill out an online questionnaire about the tools they used. At the conference, we will present the answers to this questionnaire in detail.

Conclusions and Possible Next Steps

The PAAR-net efforts suggest democratising innovation in the future as per the needs of our ageing society. Including older adults as "experts-by-experience" can help overcome the biases of youth-centric design and the technology will be more universally accessible. Generative AI can largely benefit a person's health and social connection. However, it should be designed on a "human-in-the-loop" philosophy so as not to weaken the agency and critical thinking of seniors. By 2027, the legacy of the COST Action will be a set of practical tools, including co-creation guidelines and training resources for the future generation of researchers. The only way to guarantee an equitable digital world is through co-designing with older people rather than designing for them. The shift in narrative around aging from decline to be managed to experience to be harnessed stands at the heart of this.

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GenAI for Cognitive Accessibility: Plain Language & Inclusive User Interaction

Breaking Linguistic Barriers with AI: Eye-Tracking Insights into Accessible Public Texts for Individuals with Intellectual and Developmental Disabilities

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Abstract

The present study constitutes the empirical component of the Horizon EU-funded iDEM project, which aims to develop an application based on Large Language Models (LLMs) for the simplification of complex texts to foster inclusive participation across diverse audiences. Despite the routine publication of public information intended for all citizens, access remains unequal, particularly for individuals with intellectual and developmental disabilities (IDD). The iDEM project addresses this gap by transforming complex democratic texts into accessible versions designed to reduce linguistic barriers and improve comprehension.

This study empirically evaluates whether texts processed by the iDEM system improve readability and comprehension, using an eye-tracking-based experimental design. In addition, it seeks to derive preliminary threshold estimates for text difficulty, contributing to an objective, data-driven operationalisation of readability. A participatory action research framework is employed, involving individuals with IDD as co-designers in the development of the experimental materials and procedures. Participants will be consulted to identify public policy topics of interest, after which selected governmental texts will be processed using the iDEM algorithm to generate simplified versions. Short passages from original and simplified texts will be presented while gaze metrics are recorded using the EyeLink Portable Duo system. Reading behaviour will be quantified using measures such as fixation duration, regressions, and average dwell time per word. Comprehension will be assessed through post-reading questions.

The results will determine whether artificial intelligence (AI)-facilitated text simplification improves reading efficiency and comprehension in individuals with IDD, thereby contributing evidence on accessible AI systems for inclusive digital communication.

Introduction

iDEM Project

Recent advances in natural language processing and artificial intelligence have enabled the development of tools that support under-represented groups by facilitating communication and dialogue within democratic spaces. Within this context, the Innovative and Inclusive Democratic Spaces for Deliberation and Participation (iDEM) project, funded under Horizon Europe, aims to develop an application that uses AI to transform complex texts into simplified versions for marginalised users (3).

The iDEM app is being built on next-generation multilingual models to address communication challenges across diverse European linguistic and social contexts. The app is intended to identify potential sources of misunderstanding and bias in messages across several European languages and for different audience groups. It is also being designed to support the automatic adaptation of texts in order to improve accessibility, clarity, and inclusiveness while reducing biased language. In addition, the app aims to provide AI-powered functionalities for the controlled generation and refinement of messages and broader forms of discourse, thereby contributing to more effective, audience-aware, and equitable communication. Thereby, iDEM aims to innovate democratic spaces with customised, user-centric

technology enhancing the participation and representation of marginalised groups by providing unbiased and inclusive technology.

Project aim

This study aims to test the iDEM app's effectiveness in producing accessible texts and information using empirical-experimental methods and real-world user data to quantitatively measure whether the iDEM technology and underlying LLMs and AI truly lead to a better understanding of democratic and public texts by persons with IDD.

Our Work

Background

Around six million people in the EU and 90 million people globally are effectively excluded from deliberative and participatory processes because the language and information used in these processes is not accessible to them. Democratic and public texts and information are marked by complex linguistic characteristics with high demands regarding semantic, morpho-syntactic, and pragmatic structures that make it impossible for persons with intellectual and developmental disabilities (IDD) to understand them.

In 2024, the Maltese government published 58 public consultations inviting all residents to provide their views, comments, and feedback on national strategies, policies, and reforms. However, none of these consultations were accessible to persons with intellectual disabilities because the language used was overly complex. As a result, many individuals were unable to understand the issues under consideration, formulate an informed opinion, or exercise their democratic right to participate in decision-making processes on matters that directly affect their daily lives.

Current AI tool development in this field remains largely at the prototype stage or within controlled settings, limiting the availability of real-world user data from target populations, particularly persons with IDD. Furthermore, many existing tools lack sufficiently inclusive features to meet the needs of users with disabilities (9). Moreover, AI algorithms are only as good as the data that is fed to them. Current Easy Language texts are mostly based on expert opinion and not on empirical user data (6). Hence, it remains unclear whether the AI output indeed facilitates understanding for real-world users. Using empirical-experimental methods, this study aims to fill this gap by providing objective validation for an AI tool that is currently being developed: The iDEM app.

The present study uses eye tracking in an experimental setting to record the target user group's eye gaze patterns during reading to truly test if the iDEM app is increasing both readability and comprehension of the democratic texts it simplifies. Our experiment is the first to employ eye-tracking measures to validate AI-LLMs, and therefore through our experiment the iDEM app will be substantiated with real-word data, whilst directly involving users in the development and research process.

Project description

An objective empirical-experimental methodology for assessing reading behaviour is eye tracking. Due to its non-invasive nature, eye-tracking technology has emerged as a valuable tool for investigating visual attention, cognitive processes, and language processing. Eye tracking offers an objective and low-demand alternative to traditional introspection-based methods, particularly for individuals with IDD. It does not require overt responses from participants but instead allows conclusions about text comprehension to be inferred solely from natural gaze behaviour during reading (1). By integrating eye-tracking methodology with AI-LLMs, this study is the first to capture real-world user data while directly involving users in the research and development process. The findings will provide evidence-based feedback

to developers, enabling further refinement of the algorithm and improving access to democratic texts and participatory processes for under-represented groups.

Methodology

Participants

Participants were recruited through a public call for participation disseminated by national organisations in the disability sector and other affiliated networks. Participants were individuals aged 18 years old or older, who are able to read English and have a diagnosis of an IDD. The study includes a sample of 25 participants. Participants were informed that support persons may accompany them for the duration of the experiment if desired. Ethical approval was granted through the ethics committee of the Faculty for Social Wellbeing at the University of Malta. Informed consent or assent was gathered alongside informed consent from any accompanying support persons before the start of the experiment. Participants received a voucher of 15€ for their participation.

Recording of eye-tracking data

We used the Eye-Link portable duo USB 1000 series (SR Research) for recording of gaze-related measures. The portable duo model was selected due to its high resolution and portability for house visits as some participants with IDD may be uncomfortable and overwhelmed in the laboratory. In addition, the head-free mode is paramount for a study with such a target population as it reduces sensory-related obstacles and ensures participant comfort. Data were recorded at a sampling rate of 1,000 Hz. Gaze estimation is based on the pupil-centre corneal reflection (PCCR) method combined with machine-learning algorithms. Reported spatial accuracy ranges from 0.15°-0.5°. Participants were offered a choice between head-free and head-stabilized modes during the eye-tracking procedure. In head-free mode, a target sticker was placed on the participant's forehead between the eyes, whereas the head-stabilized mode involved the use of a chin rest to minimize head movement. This option was intentionally provided to accommodate participants' individual sensory preferences and comfort needs, allowing them to select the setup they found most suitable. While a preference was given to the head-stabilized mode to optimize data quality, participant comfort and autonomy were prioritized throughout the procedure. The EyeLink Portable Duo eye tracker was selected specifically because it supports these flexible accommodation options, making it particularly suitable for use with participants with IDD.

A nine-point calibration and validation were used to ensure precise recording. To encourage and motivate the participants to follow the calibration, a cartoon image was used instead of a calibration dot (see Figure 1 below). Text stimuli were presented on a 15.6-inch laptop screen with 1920x1080 resolution using the Experiment Builder software (SR Research) in version 2.6.11.



Figure 1: Caroon images available in Experiment Builder version 2.6.11 for calibration

Stimulus material

Stimulus texts were sourced from official government websites and covered topics of interest to the target population (e.g., education, culture, health, social policies, legislation). Texts were informational or instructional and varied in vocabulary as well as semantic, syntactic, and pragmatic style. All texts were in English. Original texts were automatically transcribed to Easy English using the iDEM app and underlying algorithm. Both original and facilitated versions of the texts were several pages long. During focus groups, participants with IDD selected which text topics were to be used in the eye-tracking experiment. Single sentences or paragraphs were then selected from those corresponding government texts to be presented as stimuli during the reading experiment. The aim of this experiment is limited to understanding if readability and comprehension is enhanced in texts that undergo facilitation through the iDEM algorithm. If we had used full pages or longer paragraphs as stimuli, readability and comprehension would have been influenced by many additional variables beyond the scope of this experiment. These include factors extending beyond individual words to sentence-level and structural features, such as sentence length, syntactic complexity, word order, verb tense, and others. Persons with IDD were consulted to ensure that the chosen stimuli were understandable in isolation and without the broader context of the documents.

Psychometric assessments

Psychometric assessments were administered to each participant to measure potential co-variates that could influence understanding of the standard and facilitated texts irrespective of the iDEM app. We measured working memory capacity using the Working Memory Index (WMI) of the Wechsler Adult Intelligence Scale (10). Reading level was measured using the reading subtests of the Wechsler Individual Achievement Test (11). Fluid intelligence was measured using the Cognitive Scales of the Leiter International Performance Scale (7). All tests provide reliable evaluation of cognitive and academic abilities through a broad range of subtests and offer robust standardized data, making them gold-standard measures in the field due to their strong psychometric properties including high validity and reliability.

iDEM algorithm

The iDEM app utilises autoregressive LLMs with a decoder-only architecture, using zero-shot prompting to simplify text. Autoregressive models generate text by iteratively predicting the next word based on the previous words. Due to this, output is coherent and consistent over long passages (3).. Through zero-shot prompting, the model can perform tasks directly from instructions without task-specific training (3). Texts are simplified to three levels, easy, easier and very easy, which correspond to plain language, easy language, or easy read. These levels align with the common European system or reference for languages (CEFR) at B1, A2 and A1 respectively (4). The algorithm is currently a prototype which is implemented using the CAPITO platform and is available as a beta app on Apple and Android.

Following user feedback, the app will be redeveloped as a webservice. The prompt implemented within the app can be found in Saggion et al. (3, 2026, pp. 17-18).

Procedure

Participants were first assessed using psychometric tests to measure relevant co-variates as described above. The order of assessments was counterbalanced across participants to account for order effects. Psychometric assessments did not last longer than 1 hour (excluding breaks). In between each assessment, a break determined in length together with the participant and their support person was introduced. Depending on the participant, either in a separate session or after an extended break, the eye tracking experiment was conducted.

Participants were seated comfortably in a dimly lit room at a distance of 80 cm in front of a laptop. The eye tracker was mounted on the presentation laptop (see Figure 2). The experimenter was seated across the participant and controlled the experiment using a host laptop. The support person was asked to sit behind and out of view of the participant so as not to distract them from the task. Participants were introduced and familiarised with the eye tracker, and the procedure of the experiment was explained to them using Easy English and visuals to foster understanding. The eye tracking experiment started with a calibration and validation of the eye gaze data. If calibration or validation failed, they were repeated up to a number of four times. Upon successful calibration and validation, text stimuli were presented on the laptop screen in black font on grey background using a serifed typeface for extra legibility. Typeface and font size were chosen together with persons with IDD during the focus group. Participants would read a mix of original text samples (sourced directly from government websites) and facilitated text versions (samples that went through simplification via the iDEM app).

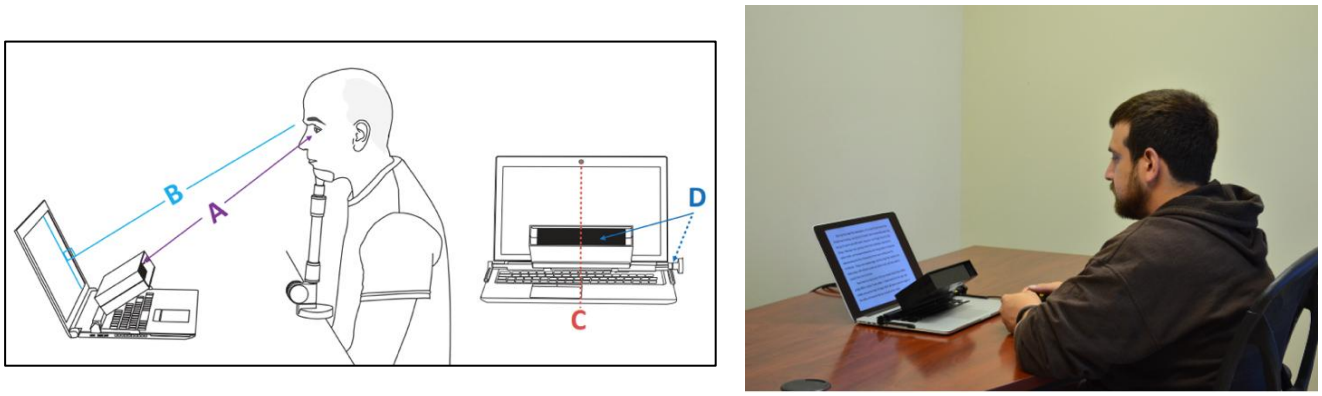


Figure 2: EyeLink Portable Duo laptop mount position displayed with chin rest on the left and without the chin rest in head-free mode on the right

After the presentation of the text stimuli true or false questions are shown at random to increase attention and to assess comprehension, and participants were asked to respond to each question. Stimuli were presented in a Latin Square Design to control for repetition effects. Each participant was presented with each text in only one condition (standard or iDEM-facilitated). Assignment of text conditions to participants was counterbalanced to ensure that each text in each condition was seen by the same number of participants. Text comprehension is measured via average dwell time per word, number of fixations per word and number of regressions per screen as well as via accuracy scores in the comprehension questions.

Conclusions and Possible Next Steps

Data analysis

Data will be analysed using the Data Viewer software (SR Research) and RStudio in version 2026.01.0. Using the Data Viewer software, first-run dwell time, fixation and regression counts will be exported as a Data Viewer report and further processed in R Studio. Using the eyetrackingR package (2), data

were down sampled to 256 Hz. Trials with a track loss of more than 25% were excluded from further analysis. For each condition (standard vs. facilitated), average dwell time per word, number of fixations per word and number of regressions per stimulus were computed. For each participant, a comprehension accuracy was computed as the percentage of comprehension questions answered correctly. To examine whether iDEM-facilitated texts are indeed easier to read, dependent variables (average dwell time, number of fixations per word, number of regressions per stimulus, comprehension accuracy) were analysed using a linear mixed-effects model with text condition (standard versus facilitated) as a fixed effect and working memory score, reading level and fluid intelligence as measured via the psychometric assessments as covariates. Co-variates account for influences of inter-individual differences. By-participant random intercepts and random slopes for text condition were included to account for repeated measures and inter-individual differences.

Expected results

As data collection is currently ongoing, at the time of submission we are unable to present any results. It is expected that the facilitated texts will yield shorter average dwell times per word, lower number of fixations per screen indicating that the facilitated texts are indeed easier to read. Alongside this it is expected that the comprehension questions will have higher accuracy answers for the facilitated texts compared to the original texts, showing that the iDEM app increases readability and comprehension of the texts (see Figure 4).Covariates will be analysed on an exploratory basis.

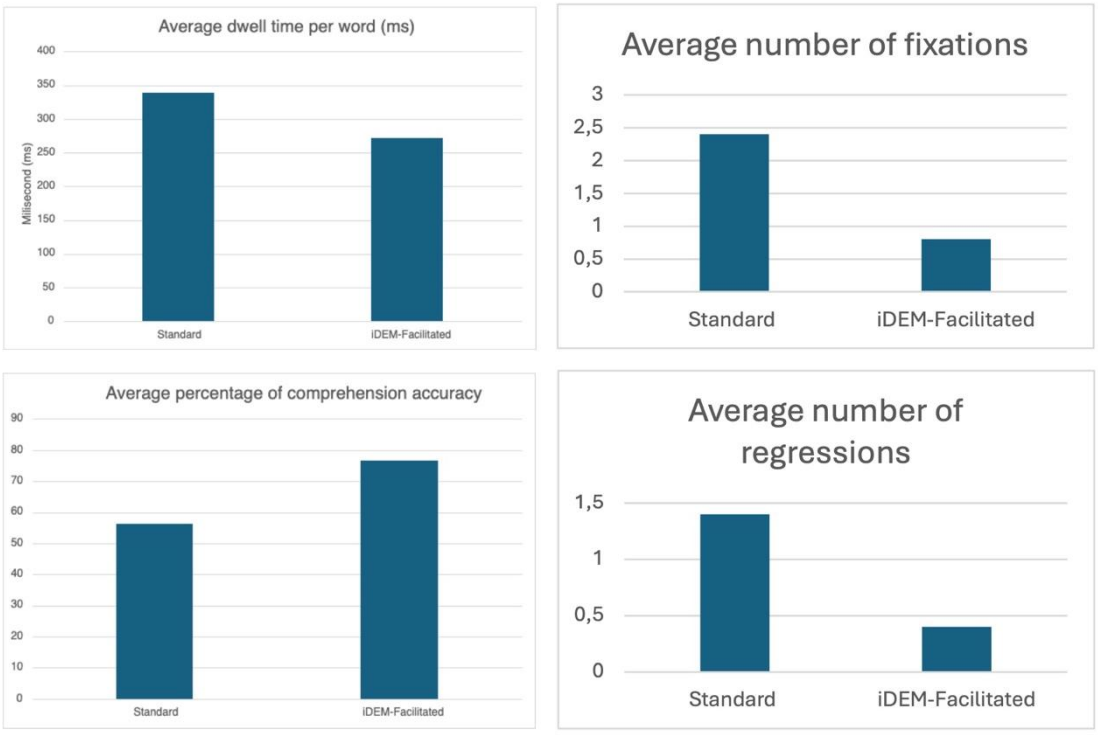


Figure 3; Graphical representation of expected results depicting iDEM Facilitated texts yield shorter average dwell times per word, less average number of fixations and regressions and increase accuracy of comprehension question answers.

Acknowledgements

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Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

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The Impact of Cognitive Accessibility on Mental Health

Creating a Recreational Environment with VR Technology for Informal Dementia Caregivers

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Abstract

Informal caregivers of people living with dementia face persistent emotional strain, stress, and social isolation due to the continuous demands of caregiving. Although exposure to natural environments and companionship have been shown to support emotional well-being, caregivers often lack access to restorative outdoor experiences or the capacity to care for pets. Virtual Reality (VR) offers a promising alternative by enabling immersive, controlled environments that can simulate nature and social presence. This paper presents the design, implementation, and evaluation of a standalone VR application developed to support relaxation and emotional relief for informal dementia caregivers. The system combines a calming virtual forest environment with an interactive virtual dog designed to evoke companionship through simple, emotionally meaningful interactions. The application was developed using Unity and optimized for the Oculus Quest 2 headset to ensure accessibility and stable performance without reliance on external hardware. The system was evaluated through both technical testing and user testing involving 63 participants from Hungarian and Portuguese caregiver groups. Quantitative and qualitative feedback was collected to assess usability, emotional impact, and perceived relaxation. Results indicate that the interactive virtual companion significantly enhanced emotional engagement and relaxation compared to passive observation of the environment alone. Participants reported high levels of comfort, ease of use, and positive emotional response, with no cases of motion sickness or major usability issues. The findings suggest that integrating virtual companionship into immersive natural VR environments can provide meaningful emotional support for caregivers. This work demonstrates the potential of VR-based recreational experiences as accessible, non-invasive tools for caregiver well-being and highlights opportunities for future development in personalized and long-term virtual therapeutic solutions.

Keywords: Virtual Reality, Informal Caregivers, Dementia Care, Virtual Companions, Emotional Well-being, Relaxation

Introduction

Dementia is a progressive condition characterized by cognitive decline that affects memory, reasoning, and daily functioning [1]. As populations age, the number of individuals requiring long-term care continues to rise, placing increasing responsibility on informal caregivers, most often family members. These caregivers provide extensive daily support, including personal care, household tasks, emotional reassurance, and medical supervision. While home-based care can improve outcomes for individuals with dementia, it frequently results in elevated stress, emotional fatigue, and social isolation for caregivers [2-5].

Previous research has demonstrated that exposure to natural environments can reduce stress and support emotional recovery [6]. Forests, parks, and other green spaces offer restorative benefits, including reduced anxiety and improved mood. However, caregivers often face significant barriers to accessing such environments, including time constraints, physical exhaustion, and caregiving responsibilities that limit mobility.

In parallel, companionship has been identified as an important protective factor against loneliness [5-9]. Interaction with animals, in particular, has been shown to foster emotional comfort and a sense of connection [12]. For caregivers, however, pet ownership may not be feasible due to additional responsibilities and logistical challenges.

Virtual Reality technology offers new possibilities for addressing these challenges [7-8]. VR enables users to experience immersive environments independent of physical location and can simulate both natural settings and social interaction. While VR-based relaxation systems and virtual pets have been explored independently, limited research has investigated their combined use for supporting informal dementia caregivers.

This study addresses this gap by examining whether a virtual forest environment enhanced with an interactive virtual dog can provide greater emotional benefit than a non-interactive virtual environment alone.

Methodology and System Design

Design Approach

The VR system was designed with two primary objectives:

1. to create a calming, immersive natural environment suitable for relaxation, and
2. to integrate an emotionally supportive virtual companion that encourages engagement without cognitive overload.

A user-centered design approach was adopted, focusing on simplicity, accessibility, and emotional impact. The application was developed for the Oculus Quest 2 standalone VR headset to ensure ease of use without requiring external hardware or technical expertise.

Virtual Environment Design

The virtual environment represents a forest landscape designed to evoke calmness and immersion. Due to hardware constraints, the environment was optimized to appear expansive while remaining computationally efficient. Several techniques were used:

1. Curved paths to create the illusion of a larger environment
2. Dense vegetation and occlusion elements to enhance depth perception
3. Spatial audio including birds, wind, and natural ambient sounds

Movement was intentionally designed to be slow and natural, encouraging mindful exploration and reducing the risk of motion sickness. Lighting was pre-baked to reduce computational load, and Level of Detail (LOD) techniques were applied to maintain performance while preserving visual quality.

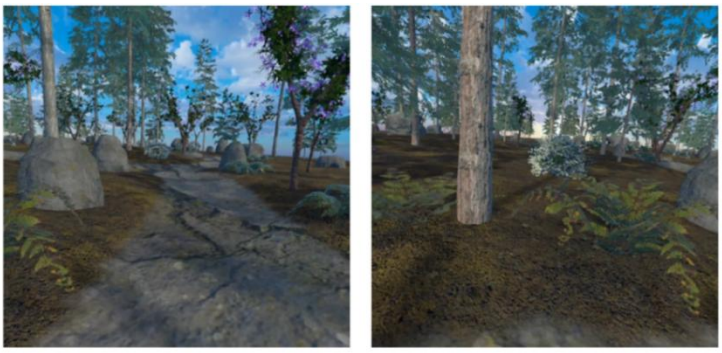


Figure 1 Forest environment

Virtual Companion and Interaction Design

A virtual corgi dog was implemented as the companion element due to its friendly and approachable appearance. Dogs are commonly associated with emotional comfort and companionship, making them a suitable choice for supporting user well-being in a virtual environment. The goal was to create a sense of connection through simple, intuitive interactions without overwhelming the user.

The virtual dog was designed with natural and recognizable behaviors, such as tail wagging, attentive movement, and responsive reactions to user actions. These elements help reinforce the feeling of presence and enhance emotional engagement, while keeping the interaction accessible for users with limited experience in VR.

Three primary interaction types were implemented:

- Petting interaction, where users can touch the dog, triggering calming animations and subtle audio feedback to simulate real-world interaction.
- Playing fetch, allowing users to throw a virtual object that the dog retrieves and returns, introducing a playful and engaging element.
- Following behavior, where the dog walks alongside the user, maintaining proximity and reinforcing a continuous sense of companionship.



Figure 2: Dog interactions

These interactions were intentionally kept simple to ensure usability and avoid cognitive overload. By focusing on a small number of meaningful and easy to understand actions, the system supports emotional engagement while remaining accessible to a broad range of users, including those unfamiliar with VR technology.

System Architecture

The application follows a modular architecture consisting of three main components:

- **Environment module**, responsible for rendering and spatial audio
- **Interaction module**, handling user input and object manipulation

- **Companion Behavior module**, controlling the behavior and animations of the virtual dog

The integration of these modules ensures smooth interaction flow and consistent system performance. Optimization techniques such as texture compression, baked lighting, and efficient scripting were applied to maintain stable frame rates.

Design Rationale

Key design decisions were based on both technical constraints and therapeutic considerations. The forest environment was selected due to its well-documented calming effects and its ability to promote relaxation through exposure to natural elements. A dog was chosen as the virtual companion because of the strong emotional associations humans typically have with pets, particularly in terms of comfort, companionship, and stress reduction [12]. The complexity of interactions was intentionally minimized in order to reduce cognitive effort and ensure accessibility for users with limited experience in virtual reality environments. These design choices ensured that the system remained accessible, intuitive, and emotionally effective, while maintaining a balance between technical feasibility and user-centered therapeutic goals.

Results and Discussion

Technical Evaluation

Technical testing confirmed that the application operated reliably on the Oculus Quest 2. The system consistently maintained the target refresh rate, remained within acceptable memory limits, and exhibited stable CPU and GPU usage. No crashes or critical performance issues were observed during extended use or repeated interactions.

User Testing

User testing was conducted with 63 participants from Hungarian and Portuguese groups. Each participant used the system for approximately 10-15 minutes and subsequently completed a structured questionnaire designed to evaluate usability, emotional impact, and overall experience.

The results indicate that participants generally experienced high levels of relaxation and reported the system to be easy to use. Users expressed positive emotional responses throughout the experience, with many highlighting a strong sense of engagement when interacting with the virtual dog. The presence of the companion was frequently associated with increased enjoyment and a greater feeling of connection within the virtual environment.

Importantly, no cases of motion sickness or severe discomfort were reported during the testing sessions, suggesting that the system design successfully supports both usability and user comfort.

User Experience Analysis

The results indicate that interaction plays a critical role in enhancing emotional engagement in virtual environments. While the forest environment alone provided a calming experience, the addition of the virtual dog significantly increased user involvement and perceived companionship. Participants frequently described feelings of comfort and emotional connection when interacting with the dog. Observations during testing showed visible emotional responses, such as smiling and active engagement.

The results were consistent across both participant groups, suggesting that the benefits of virtual companionship are not culturally dependent but reflect general human responses to social interaction and natural stimuli.

Summary of User Feedback

The quantitative results of the user testing are summarized in Table 1. The participants reported high levels of relaxation and ease of use, with more than 80% of users indicating positive experiences in these categories. A majority of participants also reported that the presence of the virtual dog improved their experience, highlighting the importance of interactive elements in enhancing engagement. Approximately 60% of users indicated a willingness to use the system regularly for relaxation purposes. The data reveals a clear trend: interaction significantly enhances the effectiveness of VR-based relaxation experiences, suggesting that the integration of a virtual companion provides added emotional value beyond passive environmental exposure.

Table 1: Quantitative results of the user testing in percentage (%)

Category	**Hungarian Group (%)**	**Portuguese Group (%)**
Ease of Use	83%	80%
Felt Relaxed During VR Experience	92%	88%
Preferred the Virtual Dog	75%	70%
Dog Enhanced the Experience	67%	65%
Would Use Regularly for Relaxation	58%	60%

Limitations

Several limitations should be considered when interpreting the results of this study. First, the duration of the testing sessions was relatively short, with participants interacting with the system for approximately 10-15 minutes. While this was sufficient to evaluate immediate usability and emotional response, it does not provide insight into long-term effects.

Second, although the sample size was adequate for initial evaluation, a larger and more diverse participant group would improve the generalizability of the findings. The study did not assess long-term usage patterns or sustained emotional benefits over time. The novelty effect of virtual reality may have influenced participants' responses, as initial exposure to immersive environments can lead to heightened engagement and positive reactions.

Future research should address these limitations through longitudinal studies involving larger participant groups, with a focus on evaluating long-term emotional impact and real-world applicability.

Conclusion and Possible Next Steps

The study demonstrates that a virtual reality system combining natural environments with interactive virtual companionship can provide meaningful emotional support for informal dementia caregivers. The findings confirm that interaction plays a key role in enhancing user engagement and relaxation, with participants reporting more positive experiences compared to passive virtual environments.

The system's design emphasizes accessibility, simplicity, and emotional effectiveness, making it suitable for real-world application. By removing common barriers such as limited time, restricted mobility, and the responsibilities associated with pet ownership, VR-based solutions can offer caregivers an accessible and practical method for stress relief and emotional support.

Future work should focus on extending the capabilities of the system and further evaluating its long-term impact. Potential directions include expanding interaction features to increase engagement, improving the behavioral realism of the virtual companion through advanced AI techniques, and introducing customizable environments tailored to individual user preferences. Longitudinal studies with larger participant groups are needed to assess sustained therapeutic effects and real-world usability over time.

These findings demonstrate the potential of VR as a non-invasive and scalable solution for supporting caregiver well-being, particularly in contexts where access to traditional relaxation methods is limited.

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SESSION

Universal and Inclusive Research,
Design and Development

Robot Design for Children with Disabilities' play: A Pedagogical Contribution

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Abstract

Play is a fundamental right and a key element for child development; however, children with disabilities often face barriers that limit their access to meaningful and inclusive play opportunities. The Family of ROBots for children with disabilities (FROB) project aims to promote inclusive "play for the sake of play" among children with disabilities within educational contexts by designing, implementing, and testing modular robotic systems and related play scenarios based on practical, symbolic, constructive, and rule-based play. The study adopts a spiral design model involving two iterative experimentation phases (S1 and S2) conducted across 12 schools, 25 classes including 27 children aged 3–9 with physical disabilities or autism spectrum disorder. The findings of the first phase (S1) informed a redesign process leading to the second phase (S2), in which structured interaction scripts were integrated alongside technological, scenario and setting design. The proposed framework emphasizes the role of the "human-in-the-loop," assigning adults and peers specific mediating functions to scaffold children's play. Drawing on dynamic assessment principles, the interaction scripts incorporated prompts, role definitions, and adaptive support aligned with children's competencies. Quantitative and qualitative data, including observational measures of enjoyment, indicate that robot-mediated play in S2 (symbolic and rule-based scenarios) resulted in significantly higher enjoyment compared to equivalent non-robot activities. The findings highlight the importance of integrating technological, contextual, and pedagogical dimensions in the design of human–robot interaction. The study contributes to addressing the lack of explicit pedagogical frameworks in educational robotics, proposing a structured approach that enhances both inclusivity and meaningful play experiences.

Introduction

The FROB project (Family of ROBots for children with disabilities)[4], coordinated by the University of Bergamo in collaboration with the University of Siena and the Politecnico di Milano, is based on the awareness that play is essential for children's development [1, 2], and is recognized as a fundamental right of every child [3]. However, children with disabilities often encounter barriers that limit their access to inclusive play opportunities [4].

The project aims to promote the right to play for children with disabilities and to expand inclusive opportunities for "play for the sake of play" [5] among children in preschool and the early years of primary school. This goal is followed through the design, implementation, and testing of modular robots, and the development of a repertoire of inclusive play scenarios reflecting different types of play and complexity. In parallel, the project investigates play within educational contexts with a dual aim: first, to identify children's play needs in order to inform and refine the design process; and second, to contribute to the theoretical understanding of play as a scientific topic, with a focus on child-robot interaction. Both the family of robots and the set of play scenarios were developed on the basis of the

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COST Action LUDI – Play for Children with Disabilities (2014–2018)[5] classification of children's play development that proposes four types of play (practical, symbolic, constructive and rule-based play) and were subsequently experimented within inclusive educational settings.

The project followed a spiral model [6], in which the robots and play scenarios were first introduced into the school context during the initial experimentation phase (S1), by implementing two types of play (practical and construction). The results obtained from S1 informed the redesign of both the robot technological aspects and the scenarios, which were then implemented in a second experimentation phase (S2) focused on the other types of play (symbolic and rule-based). Indeed, the main findings of S1 highlighted the need to extend the design framework beyond the technological and scenario dimensions, by incorporating both an accurate analysis and organization of the setting where the play activities concretely happen and some structured interaction scripts to support adequately the children's play participation. This contribution intends to propose these pedagogical aspects as an intrinsic contribution to the robot design process, representing an unavoidable part of the design itself.

Project background

Technology represents a potential facilitator and, when appropriately designed, can support access to and participation in play for all children, including those with disabilities [7]. In particular, due to their interactive and predictable nature, robots tend to elicit spontaneous interest in children and have been shown to be useful mediators for promoting play, even in the case of complex disabilities [8].

However, the existing literature on the use of robotic technologies with children with disabilities is largely oriented toward rehabilitative contexts and is often based on studies conducted in highly controlled laboratory settings [9]. While these studies provide valuable insights, they show only limited ecological validity and reduced transferability to real-world educational environments; moreover, they focus on play-like activities rather than on "play for the play's sake".

Designing robot-mediated play for inclusive contexts, such as schools, involves challenges that extend beyond the technological dimension, requiring attention to a broader interactional and contextual aspects of Human–Robot Interaction (HRI). According to McColl [10], HRI involves not only the development of robots capable of engaging users in specific tasks, but also the study of how these interactions unfold in real-world settings, encompassing both technological and social processes. Nevertheless, this second dimension, despite the increasing number of studies in the field, remains underdeveloped. A recent insightful review [11] grounded in a systematic mapping of HRI research in educational settings, indicates that, while robots can support learning and boost student motivation, robust pedagogical frameworks for their integration remain largely underdeveloped. The authors call for more interdisciplinary and methodologically varied approaches to clarify robots' educational role, especially for learners with special needs, and to guide the design of inclusive, meaningful learning environments.

The present contribution aligns with this perspective by emphasizing the need for a more systematic integration of interaction scripting within the design of robot-mediated play, an approach that bridges technological design and pedagogical intentionality. A central element of such scripts is the explicit definition of roles for all individuals involved, as role specification structures and guides participation in the interaction. This concern is particularly relevant in light of studies on social robots, which often conceptualize the interaction as a triadic system involving the child, the robot, and a third actor, such as a teacher, therapist, researcher, or peer, as captured by the notion of "human-in-the-loop" [12]. Despite the adult's role being widely recognized as a key component of this system, it often remains under-specified, with little systematic account of the behaviours expected from this figure.

Yet the importance of adult mediation is well established in the broader literature on play and development. Since Vygotskij [13], research has consistently shown that adult support can foster the

[5] https://www.cost.eu/actions/TD1309/

emergence of more complex and mature forms of play, whereas limited or low-quality interaction tends to constrain play to more elementary levels [7]. This mediating role can be further interpreted through the theoretical-methodological framework of "dynamic assessment" [14], in which evaluation and support are not treated as separate activities but are closely intertwined and continuously adapted to the child's evolving performance. Within this framework, adult mediation takes the form of a circular feedback process: the adult modulates prompts, guidance, and scaffolding in ongoing response to the competencies the child displays [15].

Methodology

The FROB experimentation was conducted in 12 schools and involved 25 classes each including at least one child with disabilities, for a total of 27 children aged between 3 and 9 years, with physical disabilities or autism spectrum disorder, sometimes in comorbidity with other impairments.

The 24-month project followed a spiral model [6], in which the design of the robots and play scenarios was followed by an initial experimentation phase (S1). Robot design included the implementation of scenarios, defined as narratives in which one or more actors engage in goal-directed activity with an interactive robot [16], as well as the technological implementation that specifies the concrete tasks, stimuli, and robot behaviours used to operationalize the scenarios [17].

During S1, the robots were introduced into educational contexts to allow children to explore and interact with them engaging their curiosity, particularly during the initial interaction phase, and facilitating learning through discovery [18]. The insights gained from S1 informed a process of redesign, leading to a second experimentation phase (S2).

Data collection for both S1 and S2 drew on complementary methods. Structured non-participant observations were conducted to analyse children's interactions with the robots; all sessions were video-recorded to ensure accurate and consistent documentation of the observed behaviours. Children's enjoyment was assessed through an observational scale inspired by Stagnitti [19], designed to capture enjoyment as displayed by each child with disabilities. Scores ranged from 0 (no enjoyment) to 6 (maximum enjoyment), enabling comparison of robot-mediated and traditional play conditions and examination of whether enjoyment varied according to play type. Group differences were then tested using a non-parametric test for paired samples, performed in SPSS, contrasting FROB-based stations with their non-robot equivalents.

Robots and Scenarios

The robot family (Fig. 1a) was designed to support four typologies of play based on the classification of children's play development (practical and construction in S1, and symbolic and rule-based play in S2) by the implementation of two modular base robots (FROBino and FROBone) that support multiple play scenarios through the combination of their bodies with interactive modules. Play sessions were organized in four stations: two mediated by the robots and two with traditional play toys.

The scenarios were as follows:

- Practical play - "The Market": children were invited to help FROBino collect vegetables scattered around the room using a stick with a carrot attached to one end (Fig. 1b).
- Construction play - "The Maze": children were tasked with designing and building a path to allow FROBone to reach a predefined goal, placing "blocks" along the robot's route (Fig. 1c).
- Symbolic play - "The Dragon": FROBino expressed needs and desires (e.g., "I'm hungry," "I'm cold"), which children had to satisfy offering illustrated coins in order to make the robot "happy" (Fig. 1d).

- Rule-based play:
    - "The Sorcerer's Apprentice": children inserted different modules into the robot, representing ingredients for a magical potion, which triggered unexpected responses from the robot (e.g., a dance or a song), (Fig. 1e).
    - "The Basket": children took turns throwing colored balls into a basket positioned on top of FROBone. A key rule required the robot to explicitly request a red ball after every ten balls of other colors (Fig. 1f) [17].

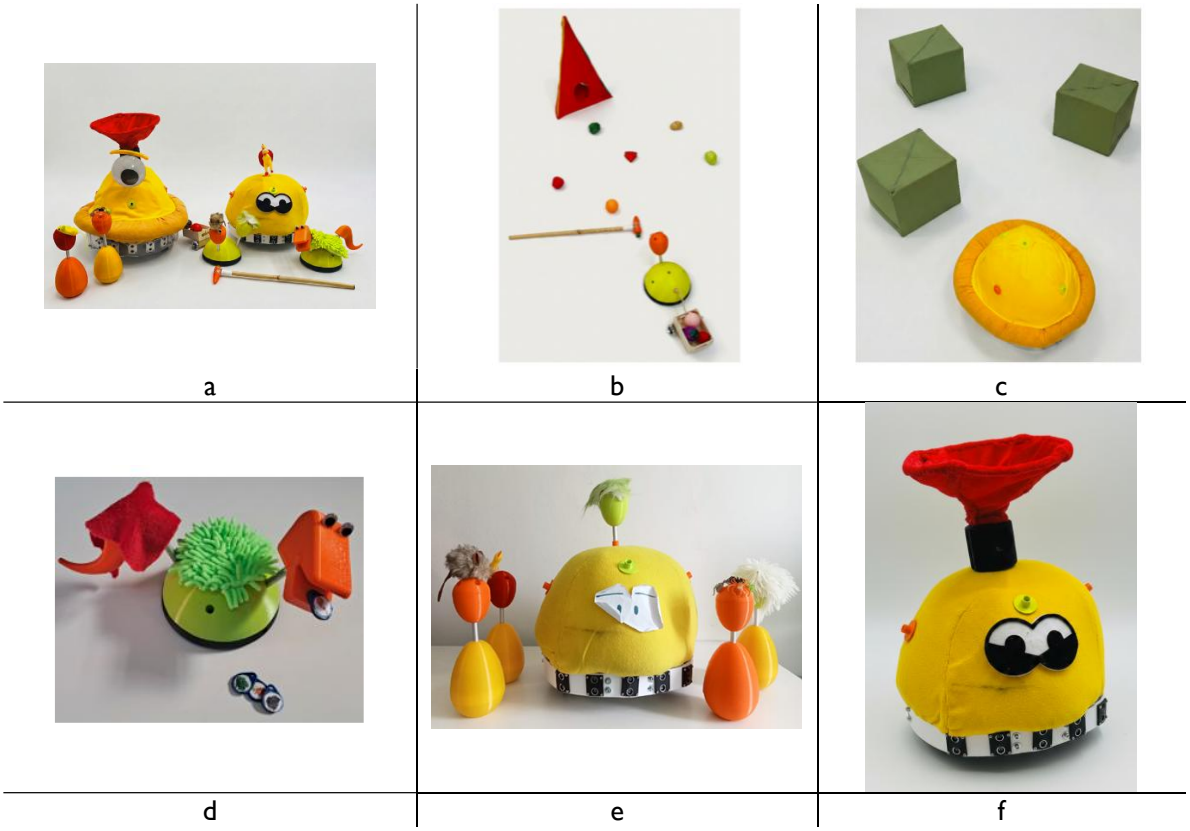


Figure 1: a: Family of Robots; b-f: play scenario configuration based on cognitive play dimensions; b: "The Market" (practice play); c: "The Maze" (construction play); d: "The Dragon" (symbolic play); e: "The Apprentice" (rule-based play); f: "Basket" (role-based play).

Project Development: The Script Introduction

The qualitative findings from the observational analysis conducted during S1 revealed that, despite an initial presentation of the robot's functioning, the adopted approach, inspired by children's discovery, often generated uncertainty within the group. Children and adults struggled both to grasp the full range of the robot's capabilities and to enact the scenario as intended. The absence of a shared script and clearly defined adult roles further contributed to an uneven and inconsistent presentation of the play activities across groups.

Children initially engaged in elementary interaction attempts grounded in simple stimulus–response mechanisms, which produced repetitive feedback loops that quickly lost their appeal and led to early abandonment of the activity. This instinctive mode of engagement also prevented children from the recognition of the different behaviors that could emerge during the unfolding of the scenario.

These findings made it necessary to revise the design model. Alongside the refinement of the setting, encompassing spatial organization, material selection, and positioning, and the scenario itself, a structured interaction script was introduced: a true theatrical prompt book conceived as a procedural guide defining roles, actions, and temporal sequencing. The script specified not only the words and phrases used to guide and sustain children's play, but also the explicit responsibilities of the adults involved:

their cues, movements, and turns on the "stage". From a pedagogical standpoint, this framework draws on the principles of dynamic assessment, which foreground the critical role of experiential contexts in supporting learning. Within this approach, adult mediation must be continuously calibrated to the competencies children demonstrate in context, given that the breadth of the Zone of Proximal Development (ZPD) is shaped by the nature and quality of the support provided.

The components redefined for S2 are presented with reference to the four dimensions of technology, scenario, setting, and script. The following section reports the most relevant elements considered, together with examples drawn from specific play activities.

The modifications introduced at the scenario level concerned three main aspects.

- Each play was framed by an introductory narrative designed to serve an immersive function. For instance, the practical play activity was introduced as follows: *"Imagine being in a market, a place full of colourful stalls, the smell of fresh fruit, and clothes and books hanging everywhere. But today a strong wind has arrived, scattering everything around: fruit, books, clothes… and now the vendors do not know how to fix the situation";*
- Play materials were redesigned to ensure greater coherence with the proposed activities through functional simplification. For example, in the rule-based play The Basket, balls and a hoop were adopted to support a more intuitive understanding of the task;
- Innovative aspects were adopted to promote the valorization of individual abilities. For example in The Basket play, children with disabilities were assigned the red ball requested by the robot and were responsible for placing it in the basket when prompted, ensuring their active and meaningful participation.

Several technological modifications were introduced to improve accessibility and child-interaction:

- additional modules were developed to support multimodal interaction, including tactile stimulation through soft materials and auditory feedback via sounds and instructional prompts, in order to broaden the range of sensory channels available to children during play;
- perceptual reference cues were added to FROB in response to children's observed difficulties in understanding the robot's perceptual orientation, that is, where it "sees" and where it "hears" likely due to its neutral form, which does not provide explicit functional affordances.
- FROB's colour scheme was also adapted to better support children with low vision;
- surfaces were enriched with differentiated textures to further facilitate tactile exploration;
- anti-fall sensors were integrated at the base of FROBino to enable safe use on horizontal surfaces such as tables, addressing safety concerns that had emerged during floor-based activities in S1.

With regard to the setting, the following aspects were identified:

- positioning of FROBino on a table surface to ensure accessibility for children using wheelchairs or unable to assume a prone position on the floor;
- selection of a relatively quiet and not overly crowded environment, given that the robot produces speech output;
- careful selection of materials and structuring of activities to minimize potential distractions; for instance, fruit used in the practical play was organized into small baskets;
- adoption of a higher and wider basket hoop to facilitate participation and improve accessibility for all children.

Finally the script focused on clarifying roles, structuring timing, and defining adult and peer support strategies:

- the roles of the adults present during the activity were established at the outset of the first station for each group;
- the guide introduced and explained the structure and organisation of the activity to the children at the beginning of each play session, providing a clear frame of reference that had been found to be lacking in S1;
- the adult was assigned explicit responsibility for recruiting and sustaining children's attention through words and behaviours, and for monitoring and ensuring each child's participation, if necessary, by introducing sequential use of different play modes or forms of interaction with the robot;
- teachers were given a scaffolding role, acting as play activators and facilitators: their support was calibrated to individual learners' needs, dynamically adjusted in response to their progress, and gradually withdrawn as autonomy increased [20, 21];
- a role was also assigned to peers; for example, children without motor disabilities were asked to bring materials closer to children with disabilities to allow their interaction with FROBino, fostering collaborative participation;
- with regard to timing, sessions were shortened from 20 minutes (S1) to 15 minutes (S2) to enhance children's focus on the activity;
- dialogic strategies were defined to support children in discovering the robot's potential through guided interaction.

It is particularly on this last point that the "mediated learning experience" was actualized. Once the setting and role management were implemented and constructed in this way, the interaction between the child and the robot was guided by prompting questions (for instance, in a scenario involving loading vegetables onto FROBino's cart, facilitators asked: "There's fruit everywhere, what could we do? Look, FROBino has a cart. Could that help? Where should we put the vegetables?") designed to enable the child to discover which game would or could be played, which behaviors the robot could offer in response to the child's own behavior, and which elements of the context could become meaningful for achieving this. This fostered a process of hypothesis generation and problem solving, which both sustained attention and curiosity and allowed the robot to be perceived not merely as a feedback provider, but as a meaningful agent within the scenario.

When children struggled, prompts were simplified to align with their ZPD; this occurred particularly with children with disabilities, for whom in some cases verbal dialogue alone was not sufficient, and it became necessary to intervene through modeling or physical assistance.

Results and Discussion

To assess the effects of robot-mediated play, at the end of each play station, a score was assigned to capture the level of enjoyment displayed by each child with disabilities. This analysis examines how enjoyment in FROB-based activities compares with equivalent play scenarios using traditional materials, highlighting the influence of robotic interaction on play experiences.

The findings show that, in S2 (symbolic and rule-based play), enjoyment levels were higher in the stations involving FROB compared to equivalent play stations using traditional materials. Tab. 1 reports these results, specifying the type of play within the cognitive dimension and whether the activity was conducted during the first (S1) or second (S2) experimentation phase. For each child, the enjoyment score observed in the FROB-based station was compared with the score obtained in an equivalent (non-robot-mediated) play station involving the same type of play. Three categories were identified: cases in which enjoyment in the FROB condition was higher, equal to, or lower than in the corresponding traditional play condition. The reported percentages refer to the total number of comparisons. For example, in symbolic play with FROBino, 10 out of 27 children showed higher enjoyment

compared to the equivalent non-robot condition (37% of the total) while 6 out of 27 children showed lower enjoyment compared to the equivalent non-robot condition (22% of the total).

The statistical results confirmed that enjoyment levels in symbolic and rule-based play were significantly higher in the FROB condition than in the corresponding traditional play activities (Wilcoxon signed-rank test, *p-value*<0.05).

Table 1: Comparison of children's enjoyment levels in robot-mediated (FROB) and equivalent non-robot play activities across different types of play (practice, construction, symbolic, and rule-based) and experimentation phases (S1 and S2). Percentages refer to the proportion of cases in which enjoyment was higher, equal, or lower in the FROB condition compared to the corresponding traditional play condition (n=27, that correspond to the number of children, for each play typology). The case in which the enjoyment level was higher than the respective traditional play were symbolic and rule-based play (light blue cells).

Play typology	Experimentation phase	FROB < traditional toys	FROB = traditional toys	FROB > traditional toys	No play	Not reported/ stations not realised
Practical play	S1	26% (7)	22% (6)	22% (6)	11% (3)	19% (5)
Construction play	S1	26% (7)	30% (8)	26% (7)	11% (3)	7% (2)
Symbolic play	S2	11% (3)	15% (4)	37% (10)	15% (4)	22% (6)
Rule-based play	S2	22% (6)	11% (3)	52% (14)	11% (3)	4 (1)

These significant findings may be attributed to a redefinition of the child-robot interaction, which was structured not only through technological enhancements to the robots and the design of the play scenario and setting, but also through the introduction of a structured pedagogical scaffolding framework, including interaction scripts that guided children's play.

In summary, the robot design process can be interpreted as the interplay of four dimensions organised across two layers, as illustrated in Fig. 2. Specifically, the process involved a scenario design layer, which includes both the implementation of the scenario and its technological realisation, and an interaction design layer, which encompasses the elements that come into play when a play scenario is concretely enacted, defined as setting configuration and the action scripts. An overemphasis on any single dimension: technological, setting, script-based, or scenario-related, may compromise the overall effectiveness of robot-mediated play.

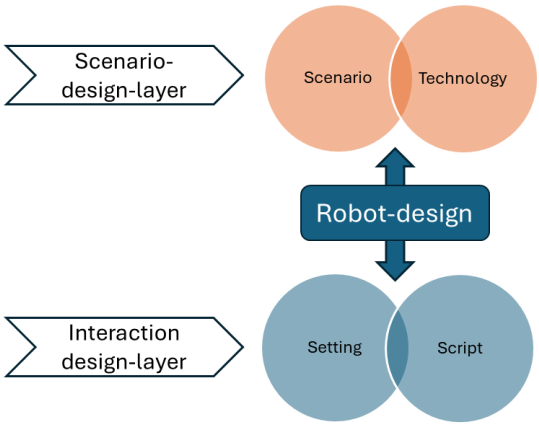


Figure 2: Dimensions considered in robot design. The effectiveness of child-robot interaction emerges from the interplay between setting, scripts and scenario.

Conclusions and Possible Next Steps

The findings related to children's enjoyment provide a further support for the effectiveness of the redesign process in which the child–robot interaction was not limited to the technological device itself, but was embedded within a structured scaffolding framework that integrated multiple dimensions. In addition to the design of the robot and the play setting, particular attention was devoted to the development of an interaction script capable of guiding and sustaining engagement. Within this framework, several elements appear to have played a crucial role, including the timing of the activities, the presence and function of the "human in the loop" and the provision of dialogic support during play. Taken together, these aspects suggest that adopting a pedagogical approach in robot-play design influences the overall experience.

As a future extension of this work, further investigation could focus on the specific contribution of each component of the proposed framework, in order to better understand the potential and limitations of integrating pedagogical scaffolding within child–robot interaction design. In particular, complementary qualitative data, such as video recordings of play sessions, could enrich the observational measures by providing deeper insights into children's engagement and enjoyment.

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From Stakeholder Voices to Design Requirements: A Co-Creation Method for the VoiceKids Approach

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Abstract

Accessible storytelling supported by Augmentative and Alternative Communication (AAC) and Text-to-Speech (TTS) requires design methods capable of translating the lived realities of schools and families into implementable software requirements. This paper formalises a co-creation method for the VoiceKids approach by combining a structured focus-group protocol with a traceable workflow for synthesising requirements from stakeholder discourse. The contribution is methodological: it does not report new empirical findings, but specifies a reproducible design-research procedure that interdisciplinary teams can adapt locally. The protocol defines purposive recruitment criteria for teachers, parents or caregivers, and therapists with direct AAC experience; a five-phase session structure; facilitation rules that manage power asymmetries and accessibility needs; and a hybrid deductive-inductive coding process grounded in reflexive thematic analysis. The paper also addresses a recurrent gap in inclusion-oriented technology work: pedagogically rich but technically unusable recommendations. To bridge this gap, coded extracts are translated into prioritised, testable requirements and organised into requirement classes relevant to software development, including functional, interface and accessibility, content-configuration, and implementation-support requirements. A concrete example shows how concerns about synthetic voice naturalness can be converted into engineering specifications for child-appropriate, configurable TTS. Analytic rigour is supported through reflexive memoing, team discussion, an audit trail, conflict documentation, and member checking rather than through inter-rater reliability claims. The resulting method supports transparent, democratic, and context-sensitive development of inclusive narrative tools for educational settings.

Introduction

Children with complex communication needs often face persistent barriers to spontaneous narration, classroom participation, and social interaction. AAC interventions can improve expressive and receptive communication, functional communication behaviours, and participation outcomes across a range of developmental profiles [1]. In parallel, current TTS systems make it possible to embed spoken output, personalisation, and multimodal feedback within digital storytelling tools. Yet these technical possibilities do not automatically produce inclusive educational practice.

Within the biopsychosocial perspective of the International Classification of Functioning, Disability and Health (ICF), disability emerges from the interaction between the individual and contextual factors,

including environmental facilitators and barriers [2]. From this standpoint, an AAC or TTS application is never neutral: it can support participation when it is pedagogically and contextually aligned, or it can become a digital barrier when it imposes excessive cognitive load, inaccessible interaction patterns, or forms of voice output that users reject.

The VoiceKids approach was developed within a wider European collaboration concerned with inclusive storytelling, teacher education, and the pedagogical use of assistive technology [3] within an ERASMUS+ KA220 project. Its rationale is that narrative activities supported by symbols, speech output, and flexible digital interfaces can enhance agency, expression, and participation for children whose communication opportunities are otherwise constrained. However, one long-standing problem remains: pedagogical recommendations are often formulated at a level that is meaningful for educators but insufficiently precise for software designers and engineers.

This paper responds to that problem by formalising a co-creation method that moves from stakeholder voices to engineering-ready design requirements. The aim is not to present a finished product, but to provide a rigorous and reusable procedure for eliciting, analysing, and translating stakeholder knowledge into specifications that can guide the development of AAC/TTS storytelling tools.

State of the Art and Rationale

The proposed method is grounded in three complementary traditions: inclusive pedagogy, participatory design, and requirements engineering. First, Universal Design for Learning (UDL) provides a relevant pedagogical foundation because it frames learner variability as a predictable design condition rather than an exception to be retrofitted later. Its emphasis on multiple means of engagement, representation, and action or expression is especially pertinent to symbol-supported storytelling and multimodal access [4].

Secondly, participatory design recognises that expertise is distributed across stakeholders and that design quality depends on the meaningful involvement of those who live with the practical consequences of technology [5]. In disability-related design, this is particularly important because educational, therapeutic, and family contexts shape use in different ways. Research on participatory design with children with special needs further shows that co-design must address communication asymmetries, mediation, and the need to bridge different perspectives without erasing them [6].

Thirdly, focus groups remain a well-established way of eliciting situated accounts, comparisons, and negotiated meanings across stakeholder groups [7]. However, generic focus-group guidance does not in itself solve the key translational challenge: how to move from rich qualitative material to requirements that are clear, testable, and traceable. Requirements engineering standards emphasise the need for explicit information items, quality attributes, and traceable requirement statements [8], while agile-oriented work on user stories reminds us that stakeholder needs must be converted into concise and actionable specifications [9].

The novelty of the present contribution therefore does not lie in claiming an entirely new qualitative method. Rather, it lies in integrating these traditions into one auditable workflow tailored to AAC/TTS storytelling. Compared with a generic focus-group manual, the present protocol is specifically adapted in four ways: it uses stimulus materials such as symbol-supported stories and TTS-enabled prototypes; it recruits across the school-home-therapy ecology; it addresses AAC-specific issues such as symbol density, access methods, and voice naturalness; and it produces requirement classes directly usable in software development.

Methodological Contribution and Scope

This contribution is a methodological design-research paper. It does not report a completed intervention study, a product evaluation, or claims of statistical generalisability. Instead, it formalises a

reproducible workflow intended for transfer and adaptation across educational and linguistic contexts. The method is procedurally reproducible in the sense that the steps, roles, and outputs are specified; it is not presented as already validated across all settings.

The paper also clarifies the issue of user involvement raised in the review process. The present article does not report direct participation sessions with children. Rather, it defines a first-stage co-creation protocol centred on adult stakeholders with direct AAC experience: teachers, parents or caregivers, and therapists. This choice reflects the need to capture contextual constraints and pedagogical routines in school, home, and therapy environments. At the same time, the absence of direct child participation is treated as a substantive limitation and an agenda for future methodological development, not as a point to be obscured.

Co-Creation Protocol

Participant recruitment follows purposive sampling. The protocol recommends mixed groups of six to twelve participants, a range that is large enough to generate interaction and contrast, yet small enough to avoid fragmentation and domination. The recommended composition combines: teachers and support teachers who understand classroom routines and curricular integration; parents or caregivers who understand acceptability, portability, and continuity of use across everyday life; and therapists or speech and language professionals who contribute clinical and developmental expertise relevant to AAC use.

Each session is designed as a structured but dialogic encounter. The moderator uses accessible language, avoids discipline-specific jargon where possible, and explicitly legitimises experiential as well as technical contributions. Questions are intended to prompt reflection; they are not treated as themes in the analysis. Themes emerge later through interpretation of patterns across participants' meaning units.

Table 1: Five-phase focus-group protocol for VoiceKids co-creation

Phase	Session component	Purpose and operational notes
1	Warm-up and ground rules	Establish a psychologically safe, non-judgemental setting; clarify aims, confidentiality, turn-taking, and the equal legitimacy of technical and experiential perspectives.
2	Stimulus-based activation	Anchor discussion in concrete artefacts such as symbol-supported stories, screenshots, prototype interfaces, or short AAC/TTS use scenarios in order to reduce abstraction.
3	Transition questions	Elicit prior experiences with AAC, expectations, frustrations, and perceived barriers related to storytelling, participation, and technology adoption.
4	Key questions	Examine pedagogical organisation, interaction with peers, personalisation needs, voice-output preferences, access methods, and practical constraints across school, home, and therapy.
5	Closure, synthesis, validation	Summarise emerging points of consensus and disagreement, invite corrections, and conduct a first-stage member check before closing the session.

Facilitation, Ethics, and Accessibility

The quality of the material produced depends heavily on facilitation. The moderator must actively manage power asymmetries between professional groups, particularly where clinical terminology or institutional authority might silence parent or teacher perspectives. Dominant speakers should be

redirected tactfully, while quieter participants should be invited to contribute through concrete prompts and examples.

Ethical and accessibility considerations should be built into the protocol from the outset. Recruitment materials, consent forms, and session scripts should be available in accessible and comprehensible formats; participants should be asked in advance about accommodation needs; and stimulus materials should be selected with readability and communicative accessibility in mind. Sessions should be audio-recorded only with informed consent, accompanied by field notes on contextual conditions, interactional dynamics, and salient non-verbal reactions.

From Reflexive Thematic Analysis to Design Requirements

After transcription, the data are segmented into meaning units rather than analysed simply by question order. The protocol adopts reflexive thematic analysis because it allows the research team to interpret pedagogical, relational, and emotional meanings that would be flattened by purely mechanical coding [10, 11]. A hybrid deductive-inductive strategy is recommended: initial orienting categories may be informed by VoiceKids concerns, such as voice output, pedagogical design, personalisation, access, and implementation conditions, but analysts must remain open to themes that cut across or extend those starting points.

To address a common misunderstanding, the protocol does not treat coding reliability as inter-rater agreement. In reflexive thematic analysis, coding is an interpretive act rather than a test of coder sameness. For this reason, analytic rigour is supported through reflexive memoing, iterative team discussion, transparent documentation of coding decisions, and an audit trail linking extracts, codes, themes, conflicts, and requirement statements [10, 11]. This makes the process inspectable without claiming a positivist form of reliability that does not fit the chosen analytic logic.

A coded theme map is produced as a visual representation of relationships among stakeholder groups, coded meaning units, candidate themes, tensions, and derived requirements. It serves both analytic and communicative purposes: analytically, it helps the team examine overlaps and conflicts across contexts; operationally, it provides a bridge between qualitative findings and development planning.

Requirement Translation and Classification

Once themes are stabilised, they are converted into formal requirement statements using a traceable template such as "The system shall…". Each statement is linked back to the coded extracts and to the stakeholder group that made the issue salient. To answer the concern that focus-group data may not map neatly onto software engineering categories, the protocol classifies outputs into four practical requirement classes: functional requirements; interface and accessibility requirements; content and pedagogical configuration requirements; and implementation or support constraints. Where useful for backlog management, these statements can also be reformulated as user stories [9].

Table 2: Illustrative translation from stakeholder voice to engineering-ready requirements

Analytic theme	Illustrative stakeholder extract	Derived requirement statement	Requirement class
Voice output concerns	"Children refuse to narrate with the tablet because the synthetic voice sounds like an adult robot and has no expression."	The system shall provide selectable child-appropriate TTS voices with adjustable prosody and expressive parameters.	Functional / interface
Pedagogical load and symbol density	"During shared reading, fifty symbols on one screen create too much cognitive load; I need to hide what is not needed for that story."	The system shall allow educators to dynamically show, hide, or scaffold symbol sets according to	Content / pedagogical configuration

		activity goals and learner profile.	
Motor access barrier	"The swipe needed to turn pages is impossible for some pupils with cerebral palsy."	The storytelling activity shall support switch access, dwell selection, and eye-gaze or alternative pointing methods as native interaction options.	Accessibility / interface
Contextual implementation constraint	"Even a good tool will fail if it depends on stable connectivity that the school does not have."	The system should support offline operation for core storytelling functions and provide a low-maintenance deployment pathway.	Implementation / support

Handling Disagreement and Prioritisation

An important feature of the method is that disagreement is not treated as a procedural failure. In inclusive design, the priorities of teachers, parents, and therapists may diverge because they act within different ecological systems and under different forms of accountability. Rather than forcing premature consensus, the protocol records conflicts explicitly and uses them as signals for modularity, user-profile differentiation, or configurable workflows.

Requirements are prioritised according to three criteria: recurrence across sessions, criticality for participation, and implementation feasibility. A final member-checking step returns the synthesised priorities to participants through a validation summary or follow-up exchange, thereby reducing the risk that the researchers' translation distorts stakeholder intent.

Outputs and Traceability Artefacts

The protocol generates four main outputs for software and design teams. First, the coded theme map visualises major themes, subthemes, conflicts, and cross-context relations. Secondly, a requirements catalogue links each requirement to its source extracts and stakeholder group. Thirdly, a risk and barrier list records infrastructural, organisational, and usability constraints such as weak connectivity, insufficient training time, or fragile hardware. Fourthly, an evaluation checklist converts prioritised requirements into review criteria that can be used in prototyping, quality assurance, and iterative refinement.

These artefacts are intentionally implementation-independent. They do not prescribe one platform, but they do preserve traceability from stakeholder voice to design decision. This is the key research contribution of the method: it creates a disciplined bridge between qualitative insight and development practice.

Discussion

The proposed method has implications beyond software requirements. By inviting teachers, parents, and therapists to articulate needs, tensions, and practical constraints together, the protocol also functions as a professional learning device. It encourages participants to reflect on their own assumptions about communication, inclusion, and technology use, and it helps interdisciplinary teams establish a shared vocabulary for design decisions.

At the same time, the method responds directly to concerns frequently raised in assistive-technology projects: that technically advanced tools are abandoned because they do not fit classroom rhythms, family routines, or access realities. By making ecological fit and traceability explicit design objectives, the protocol reduces the risk that inclusive storytelling tools remain pedagogically attractive but operationally unusable.

Limitations and Future Work

The method has clear limitations. It does not yet provide evidence of effectiveness from repeated field applications, and therefore it should not be read as validated across all educational settings. Its current form also relies heavily on adult stakeholders as proxies for children's experiences. While this is justified for capturing contextual constraints, it leaves partially unresolved the question of how children with complex communication needs can directly shape the design process.

Future work should therefore extend the protocol with child-centred participatory techniques, including tangible interfaces, multimodal prompts, observational micro-studies, and adapted co-design activities that respect different communicative repertoires [6, 12]. A further line of work is to document how the protocol must be adapted across languages, infrastructures, and national inclusion systems, so that transferability can be examined empirically rather than assumed.

Conclusions

This paper has formalised a co-creation method that translates stakeholder experience into engineering-ready requirements for AAC/TTS-supported storytelling. The contribution is methodological and practice-oriented: it offers a structured focus-group protocol, a reflexive analytic workflow, and a traceability framework that links qualitative evidence to design action. In doing so, it helps bridge the gap between the ethical aspirations of inclusive pedagogy and the operational demands of software development.

For the VoiceKids approach, the value of this method lies in making participation concrete. Stakeholder voices are not treated as background inspiration but as accountable inputs to requirement definition, prioritisation, and evaluation. This creates better conditions for developing narrative ecosystems that are accessible, pedagogically meaningful, and sustainable in real educational contexts.

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A Cross-Department, Interdisciplinary Teaching Concept for Co-Creating Assistive Everyday Technologies with People with Disabilities – Insights from a First Implementation Cycle from the NEST Project

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Abstract

This study explores *NEST* (New Everyday Supportive Technology), a cross-department, interdisciplinary teaching concept at the *University of Applied Sciences Campus Vienna* for the co-creation of assistive everyday technologies with people with disabilities. The concept addresses a persistent limitation in assistive technology education, where learning settings often rely on paper cases and provide limited opportunities for authentic user involvement, interdisciplinary collaboration, and iterative real-world development. *NEST* was designed to overcome these limitations by involving people with disabilities as active learning partners throughout all stages of the process, including needs specification, ideation, prototyping, testing, and refinement. The teaching approach combines principles of user-centred design, design thinking, and coached project-based learning.

This paper reports on the first full implementation cycle (winter term 2024/25) and presents findings from a qualitative evaluation based on a focus group with 11 students, semi-structured interviews with two learning partners and two tutors, and triangulation with project coordination feedback. The findings underline the educational value of authentic co-creation: collaboration with users increased student motivation, strengthened user-centred reasoning, and made interdisciplinary negotiation of needs, feasibility, and usability more tangible. At the same time, the study highlights structural and pedagogical challenges, particularly regarding coordination across programmes, role clarity, workload, and the feasibility of achieving highly elaborated outcomes within a one-semester format. Overall, the results suggest that interdisciplinary assistive technology education benefits from clear framing, structured onboarding, coaching-oriented mentoring, and iterative feedback structures. *NEST* thus provides a promising and transferable model for user-involving higher education in assistive technology.

Introduction

Digitalisation and technical innovation increasingly shape health and social care [1]. At the same time, higher-education courses that address assistive technology (AT) often struggle to offer authentic, interdisciplinary learning experiences: teaching scenarios are frequently based on paper cases, users are not involved, and there are limited time and infrastructure to integrate development, testing, and improvement into one coherent process. Interdisciplinary teaching formats often additionally face structural barriers, including different curricula, assessment cultures, schedules, and professional 'languages' across disciplines.

NEST (New Everyday Supportive Technology) is a cross-department teaching project at the *University of Applied Sciences Campus Vienna* with a planned duration of 5 years that addresses these challenges by developing a structured learning environment where students from engineering and health sciences work with real people with disabilities on everyday problems. The aim is to provide students the full experience of the pathway from needs assessments to co-creation, prototyping, testing in real-life contexts, and iterative improvement. Teaching is operationalised as a structured case-based learning

process: supported teamwork with regular feedback, reflection, and evaluation, where learning progress is made visible not only in outcomes but primarily in the approach taken.

State of the Art and Conceptual Background

Project-based learning and problem-based learning are widely used to foster applied competencies and professional reasoning. Interdisciplinary formats are particularly relevant in AT, because solutions must balance technical feasibility with usability, safety, everyday acceptance, and context-specific needs. User involvement is therefore a key principle: effective solutions tend to emerge when intended users shape requirements, priorities, and evaluation criteria throughout the process.

NEST integrates the principles of User-Centred-Design (UCD) [2] as well as Design Thinking: Students from the health sector are working together with students from the technology sector as a team to develop solutions for people with disabilities in everyday life. In practice, this iteratively moves through phases of understanding and observing the context, defining and refining the problem and requirements, ideating solution options, building prototypes, testing with users, and improving based on feedback. A central didactic premise is that quality and feasibility emerge through iterations—rather than through a single 'perfect' idea—while students learn to compare options using explicit criteria (benefit, effort, risks, and everyday suitability).

Methodology

Educational Design and Core Features

NEST is designed around five key elements:

- Real learning partners instead of paper cases: People with disabilities present their everyday challenges and provide feedback on ideas and prototypes.
- Co-creation as a guiding principle: Solutions are developed 'with' individuals concerned from the beginning and across iterations.
- Coaching rather than directing: Teachers from different degree programs act as mentors and provide structure and quality assurance without prescribing solutions.
- Iterative learning: Work is organized as cycles of planning, implementation, feedback, and adaptation.
- Format development as a project: Teaching formats are continuously tested and improved towards a reusable model.

Organizational Framework

The initiative is funded by the *City of Vienna* (MA23 – Municipal Department for Economic Affairs, Labour and Statistics). This external support is essential because involving real learning partners, coordinating interdisciplinary teams, and enabling development and testing requires additional resources (e.g., organisation, mentoring capacity, accessible spaces, and hardware/software). Stable conditions are established through defined roles, process-accompanying mentors, and settings for on-site and hybrid collaboration. Differences in time structures and disciplinary 'languages' are didactically used to practice requirement clarification, translation between perspectives, transparent decision documentation, and interface management.

Implementation Cycles and Participants

After an initial needs assessment that synthesised perspectives of students, teachers as mentors, and learning partners, *NEST* has been implemented in several cycles with format variety. For contextualisation, Table 1 summarises four completed, ongoing, and planned formats. The present contribution focuses on the first full implementation cycle with a semester-based course structure (Cycle A).

Table 1: Overview of NEST implementation cycles

Cycle	Format	Students	Learning partners	Output focus
A (WS 2024/25; completed)	1-semeser course	12	3	Prototypes; Tested didactic baseline (roles, team setup, feedback loops)
B (WS 2025/26; completed)	Innovation Challenge (2 days)	25	2	Five solution concepts co-created in an intensive "hackathon-inspired" format
C (SS 2026; ongoing)	Hybrid course (1 semester)	16	3	Further development of selected concepts/prototypes from earlier cycles in adapted format from cycle A
D (2026/27; planned)	Student teams; matched from a "problem pool"			Self-organized project work supported by teachers as mentors; scalable matching model

Evaluation Design

To generate first evidence on feasibility and perceived learning value, a qualitative evaluation of Cycle A was conducted after completion. Data sources comprised a focus group with participating students, semi-structured interviews with learning partners as well as tutors and additional student input. Audio recordings were transcribed verbatim and analysed using qualitative content analysis in *MAXQDA*. [3] Findings were triangulated with feedback output from coordination meetings within the *NEST* project team [4].

Results from First Implementation Cycle (Cycle A)

This section reports findings from the first implementation cycle (Cycle A), based on multiple qualitative data sources. The dataset comprises a focus group with 11 students, semi-structured interviews with two learning partners, two tutors, and one additional student interview, as well as triangulation with project coordination feedback.

The following results are presented as a thematic synthesis across data sources, covering both experienced strengths and identified areas for improvement. An overview of the consolidated themes and corresponding improvement levels is provided in Table 2.

Overall Appraisal and Engagement

Across data sources, the overall appraisal of Cycle A was predominantly positive. In the student focus group, positive statements about the project/course outnumbered negative statements in the qualitative coding synthesis. Participants frequently linked engagement to the authenticity of the case: working for a real person created a sense of responsibility and made trade-offs (e.g., feasibility vs. desirability) tangible.

Students reported that motivation tended to increase when learning partners were involved early and repeatedly, and when feedback moments led to visible iterations of the prototype. Conversely, motivation decreased when expectations about deliverables were unclear or when coordination effort limited hands-on development time.

Learning Value of Real Learning Partners and Co-Creation

Real-life collaboration with people with disabilities was described as the primary strength of *NEST*. Learning partners contributed concrete everyday constraints and priorities that reshaped initial

assumptions (e.g., what 'easy to use' means in a specific environment, or which risks are acceptable). Students highlighted that these insights were difficult to gain through desk research alone.

Co-creation required students to communicate ideas in accessible ways (e.g., using sketches, demonstrations, and simple language), to clarify expectations, and to negotiate requirements. This supported the development of user-centred reasoning: needs clarification, prioritisation, and translating feedback into explicit design changes.

Interdisciplinary Teamwork Outcomes

Interdisciplinary teamwork was perceived as beneficial but demanding. Students reported learning gains in translating between professional perspectives, aligning terminology, and documenting decisions for shared understanding. Health-science perspectives were described as particularly helpful for the students from technical programs for grounding solutions in everyday routines, safety, and acceptance, while technical perspectives supported feasibility assessment, rapid prototyping, and systematic problem decomposition.

Challenges included different expectations regarding pace and quality criteria, as well as unequal familiarity with prototyping tools or evaluation logic. Where teams established early communication routines and role clarity, collaboration was experienced as smoother and more productive.

Feasibility, Scope, and Time Constraints

A recurring theme concerned feasibility and scope. Several participants questioned whether delivering a fully 'finished' end product would be realistic within a one-semester format. Uncertainty about the expected workload was reported especially at the beginning of the course, when problem understanding and requirements were still evolving.

Time constraints were amplified by structural differences across programmes (e.g., differing calendars, part-time vs. full-time study modes, and exam periods). Fixed dates for workshops or presentations were described as challenging when they overlapped with compulsory activities. These constraints often shifted effort from development to coordination.

Role of Mentoring and Tutors, Milestones, and Feedback Loops

Mentoring in a coaching role was generally valued when it offered orientation through guiding questions and checkpoints, whereas solution-prescribing process feedback was intentionally avoided. Participants described that mentors and tutors were particularly helpful in (a) sharpening the problem definition, (b) planning realistic work packages, (c) preparing interactions and supporting communication with the learning partners, and (d) strengthening reflective documentation of decisions.

Milestones and intermediate presentations were experienced ambivalently. Some students perceived formal interim presentations as low-value compared to hands-on work, while others valued them as forcing functions for consolidation. A frequently suggested redesign was to replace a small number of high-stakes milestones with more frequent, smaller feedback loops and short deliverables (e.g., brief requirement snapshots, prototype test notes, and decision logs).

Consolidated Improvement Suggestions

Across stakeholders, suggested improvements clustered into the following actionable redesign items:

- Clearer upfront framing: communicate scope, expectations, and realistic deliverables early; emphasize prototype-oriented outcomes.
- Stronger scaffolding of early phases: structured templates for needs clarification, requirements, and evaluation criteria.

- Feedback-oriented milestone design: shorter cycles and formative checkpoints rather than few formal presentations.
- Team setup refinements: ensure adequate disciplinary representation (where feasible) and avoid overly rigid early role assignment.
- Coordination support: scheduling aligned to exam periods and program calendars; explicit communication routines and documentation standards.

Thematic Synthesis

The results were synthesised into overarching themes across data sources; a structured overview is provided in Table 2.

Table 2: Thematic synthesis of key results and improvement levels (Cycle A)

Theme	What worked well	What to improve
Authenticity & engagement	Real learning partners increased relevance, responsibility, and motivation.	Ensure early/regular user contact; clarify deliverables to avoid frustration.
User-centred competence	Needs clarification and feedback translation became tangible learning outcomes.	Provide templates for requirements and test documentation; strengthen evaluation scaffolding.
Interdisciplinarity	Perspective-taking and 'translation' across disciplines improved collaboration competence.	Support role clarity and communication routines; balance tool/skill gaps.
Feasibility & scope	Prototype-building enabled visible progress and learning-by-doing.	Adopt prototype-first logic; align scope with time/resources; reduce coordination overhead.
Mentoring & milestones	Coaching helped with framing, planning, and reflection.	Shift to more frequent, smaller feedback loops; reduce high-stakes interim presentations.

Discussion

The first full implementation cycle suggests that *NEST*'s core design choice – treating people with disabilities as learning partners and co-creators – can be a strong driver of motivation and perceived learning value in interdisciplinary AT education. At the same time, the results highlight common structural risks of cross-programme teaching: heterogeneous calendars and expectations can reduce perceived feasibility and increase workload stress if the process is not highly transparent and well-scaffolded.

From a teaching-design perspective, three levers appear central: (1) upfront clarity and structured onboarding (scope, roles, communication routines, documentation expectations); (2) realistic assessment criteria aligned with a prototype-first logic (process quality, justification of decisions, and learning evidence rather than 'perfect' products); and (3) milestone formats that privilege iterative feedback and reflective learning loops. These redesign elements also support *NEST*'s long-term goal: a reusable model that remains authentic and user-involving, yet organizationally feasible within higher-education structures.

Limitations include small samples and reliance on self-reports in the qualitative evaluation. Nevertheless, the triangulated data provide concrete guidance for format improvement and inform the design of subsequent mixed-methods evaluations across cohorts.

Conclusion and Possible Next Steps

This extended abstract introduced *NEST*, a cross-department interdisciplinary teaching concept for co-creating supportive everyday technologies with people with disabilities, and reported qualitative insights from its first full implementation cycle. Findings indicate high perceived relevance through authentic co-creation and interdisciplinary teamwork, while highlighting feasibility and coordination challenges.

Next steps will include implementing the identified improvements in ongoing and planned cycles, extending NEST into compact, challenge-based and hybrid formats. Building on an established 'problem pool', a planned 2026/27 student-team format will match challenges to students' interests, competencies and availability, while maintaining process-accompanying mentoring from health and technology disciplines. This is intended to improve scalability and curricular integration of the model.

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Inclusive research in emerging technologies: challenges and recommendations from user testing

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Abstract

Involving people with disabilities in the evaluation of emerging technologies is essential for accessibility and inclusion, yet it raises methodological and practical challenges that extend beyond technical considerations. This paper synthesises lessons learned from four user testing studies involving a virtual reality environment, an AI-based rehabilitation application, a smart TV system, and a university web platform, conducted with people with disabilities and older adults. Through a qualitative cross-case analysis, we identify eight recurrent challenge domains: recruitment and sampling, heterogeneity management, communication and consent, technological accessibility, contextual validity, measurement gaps, caregiver and third-party involvement, and micro-ethical tensions. We examine how these challenges were addressed through adaptive strategies such as community-based recruitment, flexible protocol design, iterative consent, systematic documentation of adaptations, and feedback loops with participants. Building on this synthesis, the paper proposes a set of preliminary recommendations for inclusive research practice structured around four phases: inclusive planning, accessible implementation, reflexive analysis, and equitable dissemination. This contribution offers guidance for more inclusive and ethically grounded technology evaluation.

Introduction

According to the World Health Organization [1], people with disabilities represent approximately 16% of the global population, yet they remain underrepresented in technology research and development [2]. As emerging technologies become embedded in everyday life, ensuring their accessibility is a practical necessity. In this context, accessibility extends beyond removing barriers to enabling individuals to fully benefit from technological advancements [3].

Achieving inclusive innovation requires involving people with disabilities as active participants to understand their real needs and lived experiences [4]. However, conducting research with people with disabilities presents distinctive challenges that extend beyond conventional Human-Computer Interaction (HCI) studies. Traditional research methods often fail to accommodate the diverse visual, auditory, cognitive, mobility, and dexterity needs within disability communities [5]. Consequently, studies risk unintentionally excluding participants, generating biased findings, or reinforcing inequities in design [6, 7].

While approaches such as Participatory Design (PD) and Human-Centered Design (HCD) [8] emphasize co-creation, user empowerment and iterative engagement [9, 10], their application in disability research is frequently hindered by inaccessible instruments, inconsistent guidelines, and a lack of methodological standardization [11, 12]. These challenges are further amplified when evaluating emerging technologies, which introduce new complexities such as data privacy, cognitive load, or adaptive interfaces.

The present paper builds upon multiple empirical studies conducted within an inclusive design research group. These studies encompass user evaluations across a spectrum of technologies, including a virtual reality application, an AI-based rehabilitation tool, a smart TV system, and a university web platform. By synthesising lessons learned across these projects, this work identifies recurring challenges and

proposes preliminary recommendations for inclusive research. The goal is to provide practical guidance for embedding accessibility into technology design and evaluation processes. To guide the analysis, this paper addresses three research questions: (RQ1) What methodological challenges recur across inclusive user testing studies involving emerging technologies and people with disabilities? (RQ2) How are these challenges addressed in practice across different technologies and testing contexts? and (RQ3) What preliminary recommendations can be derived from this cross-case analysis to support inclusive research practice?

State of the Art

The field of HCI and Assistive Technology has witnessed a paradigmatic shift from "researching for" to "researching with" people with disabilities, reflecting a broader reorientation towards inclusive and participatory research practices [13, 14]. This transition challenges traditional top-down models by recognising that inclusion cannot be limited to the accessibility of final products, but must also extend to the ways in which research is designed, conducted, and interpreted [10, 11].

Recent work has highlighted that research practices themselves may reproduce exclusion when they rely on implicit assumptions about people abilities, standardised participation formats, or rigid protocols [11, 15]. From this perspective, inclusion concerns not only who participates in research, but also how participation is structured and supported [16]. This gives rise to a tension between methodological standardisation and the flexibility required to accommodate heterogeneous access needs, individual pacing, and personalised support.

Empirical studies report persistent structural constraints across the research lifecycle. Recruitment strategies frequently depend on convenience sampling and established institutional or digital channels, which tend to favour participants with lower support needs or higher digital literacy, while excluding others [17, 18]. Participation may also involve burden, as standard study designs often underestimate the cognitive effort, physical stamina, or emotional labour required from people with disabilities, affecting engagement [19].

These methodological challenges intersect with ethical considerations that extend beyond formal review procedures [20]. While institutional ethics committee focus on procedural compliance, researchers regularly encounter micro-ethical dilemmas in situ, such as responding to fatigue or discomfort, negotiating consent as an ongoing process, and managing power relations when caregivers are involved [21].

Several conceptual frameworks have been proposed to address methodological challenges in inclusive research. Universal Research Design promotes proactive planning for accessibility across recruitment, consent, data collection, and analysis [22], while Disability Interactions foregrounds power relations and co-creation in disability innovation [21]. Participatory models such as Ladders of Participation further contribute conceptual tools for reflecting on degrees of involvement and agency [23]. Living Lab approaches may also complement laboratory-based testing by foregrounding real-world use, although they introduce additional methodological complexity related to extended engagement, contextual variability, and multi-stakeholder coordination [24]. Although these frameworks offer valuable high-level guidance, they often remain abstract and provide limited operational direction for implementation in heterogeneous, real-world research contexts.

These limitations become particularly pronounced in the evaluation of emerging technologies. Immersive environments may introduce physical and perceptual demands such as fatigue or sensory overload [25], while AI-based systems raise concerns related to bias, transparency, and user agency [26]. Taken together, these challenges highlight the need for empirically grounded insights into how inclusive research is enacted in practice. In such contexts, existing frameworks may offer limited support for navigating the intersection of complex accessibility needs and the dynamic, evolving nature of these technologies.

Within this landscape, inclusive research design should be understood as going beyond diverse recruitment to encompass accessible communication, flexible methodologies, and participant-centred research practices. Yet much of the existing work continues to focus on technological outcomes rather than on the inclusivity of research processes themselves. The present study contributes to addressing this challenge through a cross-case analysis of inclusive testing experiences with different emerging technologies and user groups.

Methodology

This study adopts a qualitative, reflexive methodological approach to examine the empirical challenges that arise when evaluating emerging technologies with people with disabilities [27]. Rather than focusing primarily on technological outcomes, the analysis foregrounds the research process itself and the ways in which methodological decisions can enable or constrain inclusion. The aim of this secondary analysis is not to compare the technological performance of the systems under study, but to identify recurring methodological challenges and adaptive responses across cases. Therefore, explicit attention is paid to how choices around user test phases may reproduce, reinforce, or counteract exclusion.

The reflections presented here derive from a comparative analysis of four empirical studies conducted between 2019 and 2024 within the Mondragon Unibersitatea Desing Innovation Center inclusive design research group [28]. The projects involved people with disabilities and older adults in user testing of emerging technologies supporting rehabilitation and autonomy. By synthesising lessons learned across multiple technology domains and participant populations, the study identifies recurring patterns, tensions, and strategies that transcend individual project contexts.

Across all projects, the empirical work was conducted through user testing, following a set of core methodological phases commonly described in HCI research: study planning, participant recruitment, preparation of materials and procedures, test execution and data collection, and analysis and reporting of results [10, 29]. This shared structure provided a consistent methodological basis across all studies.

All studies obtained approval from the institutional ethics committee and employed accessible informed consent procedures tailored to participants' needs (e.g., plain language documents, multimodal explanations, supported decision-making). Data collection combined user testing, observation, semi-structured interviews, and researcher field notes. Notes produced during and after sessions were used to document methodological decisions, emergent issues, and adaptations implemented in situ in response to accessibility barriers. No additional data collection was conducted for this meta-study; the analysis draws on existing documentation.

A cross-case thematic analysis through the inclusive research group was then conducted to identify recurrent challenge domains and strategies [30]. The analysis proceeded through three phases: (1) individual case review: each researcher reviewed documentations from their respective projects, identifying methodological challenges, adaptations, and lessons learned, (2) Cross-case comparison: the research team met to compare findings across projects, identifying patterns, commonalities, and divergences in the challenges encountered and strategies employed, and (3) Thematic synthesis: recurrent themes were consolidated into eight challenge domains, which were then used to structure the findings and inform the development of recommendations.

Table 1: Overview of the accessibility testing projects

Technology	Description	Sector	Participants	Year	Testing context	Objective
VR environments	Immersive physical and cognitive training activities	Health	19 people with disabilities	2024	Laboratory-based evaluation	Identify accessibility barriers and facilitators
AI-based rehabilitation app	Adaptive physical exercise programme supported by artificial intelligence	Health	10 older adults	2023	Real-world test	Evaluate user experience and daily integration.
Smart TV system	Platform offering personalised content such as reminders, relaxation exercises, and medication alerts	Health	16 older adults	2023	Real-world test	Analyse interaction patterns, user experience, and autonomy
University web platform	Higher education website tested for accessibility and usability	Education	11 people with disabilities	2022	Laboratory-based evaluation	Assess digital accessibility and inclusive user experience

The four studies included in this analysis are summarised in **Chyba! Nenalezen zdroj odkazů.**. Together, they encompass 56 participants with disabilities (visual, auditory, cognitive, mobility and dexterity) or age-related functional limitations, four distinct technology platforms, two main application domains (health and education), and two testing contexts (laboratory-based and real-world testing). Studies 2 and 3, which involved real-world testing with older adults over extended periods, incorporated elements of Living Labs approaches, including in-home deployment, longitudinal engagement, and observation of technology integration into daily routines. Taken as a whole, these studies provide a diverse empirical basis for examining inclusive testing practices across different contexts and technologies.

Results

The cross-case analysis identified eight recurrent domains of methodological challenge across the four studies (**Chyba! Nenalezen zdroj odkazů.**). These domains were not isolated obstacles, but interrelated features of inclusive user testing that affected recruitment, participation, interpretation, and the overall validity of the studies.

Table 2: Recurrent methodological and ethical challenge domains across the four studies.

Challenges	Affected studies
Recruitment and sampling: Small and dispersed populations; resource-intensive recruitment; representation imbalances	All four
Heterogeneity management: Diverse access needs; continuous protocol adaptation; limited data comparability	All four
Communication and consent: Language accessibility; verification of understanding; need for ongoing and iterative consent	All four
Device-related barriers; fatigue and overload; inherent design limitations	Studies 1, 2, 3
Contextual validity: Integration into everyday routines	Studies 2, 3
Measurement gaps: Lack of validated instruments; outcome selection; uncertain validity of adapted measures	All four
Caregiver and third-party involvement: Proxy participation; autonomy tensions; support dynamics	Studies 1, 3
Micro-ethical tensions: Situated ethical dilemmas (fatigue, discomfort, proxy influence, requests beyond the study scope); need for in-situ ethical judgement beyond formal protocols	All four

Recruitment and sampling

Recruiting participants across diverse disability profiles required long lead times, sustained collaboration with community organisations, and flexible scheduling around health, care, and work routines. Representation imbalances emerged when some groups (e.g. wheelchair users or people already connected to user organisations) were easier to reach than others (e.g. people with intellectual disabilities or those with less institutional support), raising concerns about whose experiences were actually captured in the studies. Because participation was voluntary and not financially compensated, some individuals participated in repeatedly (estimated 40% overlap across projects), which may have further limited the diversity of perspectives represented.

Heterogeneity management

Heterogeneity within and across disability profiles required continuous adaptation of tasks and procedures. A backup plan was always prepared so that activities could be modified or replaced if a participant felt uncomfortable, and researchers explored the reasons behind such difficulties. These adaptations were important to enable meaningful participation but also complicated data comparability and challenged conventional notions of standardisation and replicability. In some cases, equivalent solutions were implemented. For example, in the VR study, when a participant could not use the controllers, the researcher operated the system from the computer while the participant experienced the scenario through the headset. In VR sessions, protocol adaptations occurred in 57% of sessions.

Communication and consent

Across the four studies, communication-related challenges frequently took the form of apparent agreement, concealing partial misunderstandings. Consent and study explanations often took 2-3 times longer than anticipated and had to be revisited during the session, especially when tasks or technologies became more complex than participants initially expected. To support understanding, researchers routinely adapted their communication on the fly, reformulating questions, using concrete examples, or referring back to what had just happened in the interaction. In some cases, consent or key instructions were revisited at several points in the session when signs of fatigue, confusion, or frustration emerged.

Technology accessibility

Unlike the mature web platform, where accessibility issues typically resulted in navigational frustration, emerging technologies introduced other barriers that fundamentally disrupted participation. Especially the VR system and the smart TV interfaces introduced constraints that affected both user experience and the conduct of the sessions. VR headsets occasionally caused physical discomfort, disorientation, or visual strain, and 21% of participants chose to remove the device or stop the task before completion. Complex interaction sequences (e.g., multi-step navigation with remote controls) also led to repeated errors, and increased fatigue, requiring the researcher to simplify tasks, provide more guided support, or shorten the session.

Contextual validity

Contextual factors further shaped what was feasible. In laboratory-based testing, equipment could be adjusted and controlled more easily, but the environment was unfamiliar and sometimes anxiety-provoking for participants. In real-world home testing, performances were influenced by domestic routines, interruptions, lighting conditions, and available space. In the smart TV system, technology that seemed usable in the lab was perceived as too demanding or difficult to integrate into everyday life when tested in real-world environment. Extending the testing period also made it possible to observe patterns of use, contextual barriers, and the degree of longer-term acceptance.

Measurement gaps

Across all four studies, measurement choices proved challenging. Validated instruments that were both accessible and appropriate for participants with diverse disability profiles were often unavailable, so standard questionnaires or performance metrics had to be adapted or replaced with more qualitative indicators. These adaptations were necessary to avoid excluding participants, but they raised questions about how to interpret and compare results across individuals and studies. In some cases, tasks were simplified, scales were shortened, or items were reformulated in plain language, which improved comprehension but made it difficult to relate scores or to aggregate data in a conventional way. As a result, researchers relied increasingly on triangulation between different data sources such as observations, think-aloud comments, and follow-up interviews to make sense of outcomes and to contextualise results.

Caregiver and third-party involvement

In most sessions, participants were accompanied by caregivers, sign language interpreters, or other support persons. Their presence was often essential to make participation feasible, for instance by assisting with mobility, supporting communication, or helping to set up the technology in the home. At the same time, these arrangements altered the interactional dynamics of the study. Support persons sometimes anticipated answers, reformulated questions, or guided participants through tasks in ways that made it difficult to distinguish whose perspective was being expressed, or whether difficulties with a task stemmed from the participant or from the form of support provided. This required researchers to explicitly discuss roles at the start of each session, to consciously redirect questions back to participants and invite their own views, and to carefully note when responses appeared to be influenced or voiced by third parties.

Micro-ethical tensions

Researchers encountered situated ethical dilemmas that could not be fully anticipated in formal protocols. Examples included situations in which participants showed clear signs of fatigue but insisted on continuing; cases where participants described a task as "easy" while repeated unintentional errors suggested confusion or frustration; and home visits that revealed unmet needs beyond the scope of the study. Responding to these tensions required flexible, case-by-case judgement, team discussion, and space for reflexive consideration, rather than relying solely on procedural requirements.

Recommendations for inclusive research practices

Based on the cross-case analysis, we propose a set of preliminary recommendations for testing emerging technologies with people with disabilities. These recommendations are structured around four interrelated and iterative phases: inclusive planning, accessible implementation, reflexive analysis, and equitable dissemination.

Inclusive planning

This phase focuses on creating the conditions for meaningful and safe participation before any test is done.

1. Engage disability organisations and user groups from the earliest stages of study design to identify priorities, support participant recruitment, and build trust, using diverse outreach channels to reach a broad and heterogeneous range of participants.
2. Allocate sufficient time and resources for relationship-building, the production of accessible recruitment materials, and accommodation recognising that inclusive research typically requires more time, personnel, materials, and space than conventional studies.

3. Anticipate diversity and plan flexible locations, schedules, tasks, and formats for varied disabilities and support needs.
4. Provide training and empathy-building activities for research and design teams to enhance understanding of participants' lived experiences and to support informed decision-making during studies.

Accessible implementation

Once the study is underway, accessibility must be embedded in the practical organisation of sessions and procedures. We recommend that the research team comprise at least two members, so that one person can focus on supporting in-situ adaptations and interaction with participants while the other attends to observation and note-taking. Having two perspectives on the same session also supports more balanced interpretation and decision-making in subsequent analytical steps, helping to avoid relying solely on a single researcher viewpoint. In addition, some evaluation contexts involve autonomous use by participants, in which technologies are used independently and data are generated and recorded without the presence of a researcher; these conditions should be anticipated and designed for in advance to ensure accessibility and methodological robustness.

1. Design research environments, procedures, and instruments to be accessible by default, applying Universal Research Design principles wherever possible.
2. Allow flexible session duration, task adaptation, and breaks, with protocols that explicitly permit in-situ adjustments in response to fatigue, discomfort, or confusion, and systematically record these adaptations as part of the study data.
3. Provide multimodal consent and communication supports (e.g., interpreters, visual materials) and clarify the roles of caregivers and support persons so that they enable rather than overshadow participants voices.

Reflexive analysis.

Analysis is treated not only as a technical phase of coding and interpretation, but as an opportunity to reflect on how methods shaped the data and in the accessibility of the process itself.

1. Treat methodological adaptations, observed barriers, and protocol deviations as meaningful data about accessibility and lived experience, rather than as mere exceptions to be ignored.
2. Use mixed methods and team-based reflexive practices to interpret findings, paying attention to whose voices are centred, how support persons may have influenced data, and how the research context shaped what could be said or done.
3. Systematically document adaptations, time to time dilemmas, and researcher positionality to enhance transparency and transferability, while triangulating data through multiple methods, sources, and perspectives wherever possible.
4. Where feasible, share preliminary interpretations or summaries with participants or key informants (e.g., through member checking or feedback sessions) to verify whether conclusions reflect what they intended to communicate and to reduce the risk of misinterpretation.

Equitable dissemination

Finally, dissemination is approached as part of responsibility of inclusive research, not only as an academic output.

1. Share findings with participants, organisations, and community partners in accessible formats (e.g., plain-language summaries, short presentations, or videos), and not only through scientific publications.

2. Recognise the contributions of participants and organisations through acknowledgements, invitations to events, and, where appropriate, co-authorship or advisory roles.
3. Use the results to inform both the design and deployment of technologies and the refinement of methodological practices around inclusive research (e.g., ethics procedures, recruitment policies, training for research staff).

These recommendations are not intended as a rigid protocol, but as a set of guiding principles that can be adapted to different technologies, contexts, and populations. They emphasise that inclusive research design is an ongoing, situated practice rather than a fixed checklist, and that methodological decisions at each phase have direct implications for who can participate, what can be learned, and how just and useful the resulting technologies can be.

Conclusions and Possible Next Steps

Testing emerging technologies with people with disabilities requires more than procedural accommodations; it demands methodological innovation, ethical commitment, and sustained reflexive practice. Drawing on four accessibility testing projects, this paper has identified eight recurring challenges and synthesised a set of adaptive strategies into a preliminary recommendation for inclusive research practices. These recommendations emphasise inclusive planning, accessible implementation, reflexive analysis, and equitable dissemination as interconnected pillars of rigorous and just research. This paper contributes by focusing on how inclusive evaluation practices shape the validity of emerging technologies. The findings presented in this paper are drawn from four projects conducted within a single institution with established expertise in inclusive design, and they focus on a limited range of technologies, contexts and disabilities. As such, the challenges identified may manifest differently across other technologies, participant groups, or cultural settings.

Future work should further validate and refine these recommendations across additional technologies, settings, and disability groups, and develop practical tools and reporting standards to support their implementation. It would also be important to explore in greater depth how remote testing conditions shape participation, including the impact of the digital divide, connectivity constraints, and the need for ongoing technical support. Additionally, research is needed to develop validated, accessible measurement instruments that can support both rigorous evaluation and meaningful participation.

Finally, there is a need for greater collaboration between researchers, disability organisations, technology developers, and policymakers to ensure that inclusive research practices are not only documented but also institutionalised through funding requirements, ethical guidelines, and professional training. Rather than offering definitive answers, these recommendations are intended to support more reflective, transparent, and accountable approaches to involving people with disabilities in the evaluation of emerging technologies.

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When Accessibility Meets AI: Gender Bias in Automated Interaction Systems

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Abstract

Accessibility technologies and artificial intelligence (AI) increasingly mediate how users interact with digital systems, shaping how identity is recognized and represented. While prior work has examined gender bias in AI and interface design, limited attention has been given to how accessibility and AI jointly construct gender during interaction. This paper presents a qualitative, system-oriented analysis of this intersection, identifying two mechanisms: structural constraints in accessibility technologies that require gendered representation, and probabilistic inference in AI systems that assign gender from user data. Their interaction leads to the stabilization and propagation of gender classifications over time. Based on this analysis, we outline design considerations for more inclusive systems, emphasizing reduced reliance on mandatory gender categories, constrained use of inferred gender, and increased user control. The results highlight the need to address bias at the level of interaction between system components.

Introduction

People increasingly interact with digital systems through artificial intelligence (AI) and accessibility technologies that shape how they are recognized, interpreted, and represented during use. In these interactions, gender is not only expressed by users but is often inferred and operationalized by computational processes such as classification, personalization, and linguistic generation.

A growing body of research has shown that these processes are prone to gender bias. Studies in natural language processing, speech recognition, and computer vision report systematic disparities and misclassifications, particularly affecting gender-diverse users [2,3,12,16,18]. In parallel, work in Human–Computer Interaction (HCI) has examined how interface design reinforces binary gender norms through visual representation, language, and interaction patterns [1,4,8,15]. More recently, critical perspectives have argued that accessibility technologies are not neutral supports but infrastructures that shape how users' identities become legible within computational systems [13].

Despite these advances, limited attention has been given to how accessibility technologies and AI systems operate together in shaping gender during interaction. Accessibility features such as screen readers, voice interfaces, and personalization mechanisms are increasingly integrated with AI-driven components, influencing both how user input is processed and how system output is generated. This integration creates conditions in which gender is not simply represented but actively constructed through system behavior.

In this paper, we examine how gender bias emerges from this integration of accessibility and AI. We focus on identifying recurring mechanisms through which gender is inferred, constrained, or misrepresented in system behavior. Based on this analysis, we derive design implications to support more gender-inclusive forms of interaction.

Background and Theoretical Framing

From Gender-Inclusive Interfaces to Gendered Systems

Prior work in HCI has shown that interface design often reinforces binary gender norms through visual representation, language, and interaction patterns [1,4,8,15]. These elements shape users' sense of inclusion and belonging. More recent research has extended this perspective by examining how systems themselves participate in gender classification. Automated approaches frequently rely on simplified and essentialized representations of gender, leading to misclassification and exclusion, particularly for gender-diverse users [7]. This shift reframes gender not only as a representational issue but as a computational construct embedded in system behavior.

Accessibility as an Interaction Infrastructure

Accessibility is commonly framed as a layer of technical accommodation. In practice, accessibility technologies are deeply integrated into interaction processes and mediate how users engage with systems. From this perspective, accessibility functions as an interaction infrastructure that shapes how input is captured and how output is rendered, thereby influencing how identity—including gender—becomes technically legible. Recent work in disability justice further emphasizes how such systems can encode normative assumptions and contribute to structural exclusion [13].

AI as a System of Gender Classification

AI-driven systems rely on classification, prediction, and inference to support interaction, often involving the interpretation of identity-related attributes. Empirical studies have demonstrated that these systems reproduce gender bias across modalities such as language, vision, and speech [2,3,12,16,18]. These processes tend to treat gender as a stable and classifiable attribute, despite its social and contextual nature. When integrated with accessibility technologies, such assumptions can shape interaction in ways that constrain or misrepresent users' identities.

Methodological Approach

This study adopts a qualitative, non-empirical, system-oriented approach to examine how gender bias emerges at the intersection of accessibility and AI-driven systems. The analysis focuses on system behavior, interface outputs, and technical representations of identity, without involving human participants.

The study is informed by three complementary sources. First, we engaged with AI-driven and accessibility-enabled systems through direct interaction, observing how identity-related inputs—such as names, pronouns, and voice interaction—are processed and reflected in system outputs. The aim was not to provide a comprehensive survey of systems, but to identify recurring patterns in how gender is inferred and represented across typical interaction scenarios.

Second, the analysis draws on the authors' experiences working with accessibility technologies in research and teaching contexts, where recurring patterns of system behavior have been observed over time. These observations are further informed by informal accounts from colleagues, students, and collaborators, which help surface consistent issues across different contexts of use.

Third, the interpretation is grounded in prior research on gender bias in AI, accessibility, and HCI, which provides empirical and conceptual support for the identified mechanisms.

The analysis combines interaction-based examination of system behavior with the review of technical documentation. Systems were engaged using variations of identity-related inputs to observe how gender is inferred, assigned, or constrained in practice, with particular attention to linguistic output, personalization mechanisms, and identity-related responses. Part of the analysis was conducted in

Portuguese, a language with strongly gendered grammatical structures, allowing us to observe how systems handle gender agreement and linguistic inflection in contexts where gender is explicitly encoded.

Findings are interpreted through feminist and intersectional perspectives in HCI [7,8,15], as well as recent work on disability justice [13]. The study focuses on identifying recurring patterns in system behavior rather than measuring their prevalence or impact.

Findings and Discussion

Binary Assumptions in Accessible Interaction

Many accessibility technologies rely on interaction structures that presuppose binary gender categories, particularly in linguistic output, identity representation, and personalization mechanisms [10,9,17]. In these cases, gender is not inferred from user data but imposed as part of how systems are designed to produce output or manage identity.

One recurring pattern emerges in text-to-speech and screen reader interaction, where systems must generate grammatically correct output even when gender is unspecified. In languages such as Portuguese, where grammatical gender is pervasive, this requirement forces systems to assign gendered forms in articles, adjectives, and verb agreements. When no gender information is available, systems often default to masculine forms, effectively encoding a binary assumption into the output. Here, gender is not predicted but required by the linguistic structure of the system.

A similar constraint appears in identity management and personalization mechanisms. Many systems require users to select gender from predefined categories or rely on stored identity attributes to populate forms and profiles. In accessibility contexts, these mechanisms are often integrated with autofill, input assistance, and profile synchronization features, making them difficult to bypass. As a result, users may be forced into binary classifications or have previously stored identity information—such as legal names—propagated across systems, leading to experiences such as deadnaming.

These examples illustrate how accessibility-mediated interaction can enforce gender through structural constraints. Rather than adapting to user identity, systems require gender to be specified in predefined ways, embedding binary assumptions into the interaction process itself.

Gender Inference in AI-Driven Systems

In contrast to structural constraints, AI-driven systems introduce gender through probabilistic inference. These systems derive gender from signals such as voice characteristics, facial features, names, and behavioral patterns, treating gender as an attribute that can be predicted from data [16,3,2].

We define **algorithmic misgendering** as the assignment of a gender category through inference processes when this assignment does not reflect, or is not specified by, the user. This phenomenon can take different forms. In some cases, it appears as **classification error**, where a system assigns an incorrect gender category relative to an assumed ground truth. In other cases, it results from **unwanted inference**, where gender is inferred and operationalized despite not being explicitly provided or required for the interaction. While classification errors highlight issues of bias and model performance, unwanted inference raises broader concerns about the necessity and appropriateness of gender classification in automated systems.

This phenomenon is particularly evident in voice-based interaction, which is widely used by people with visual or motor impairments as a primary access modality. Speech recognition and voice assistant systems frequently associate vocal pitch and timbre with binary gender categories. Users whose voices fall outside expected patterns—including gender-diverse individuals and people with speech variations related to disability—may be consistently misclassified. Prior work has shown that such systems exhibit

systematic disparities across gender and dialect, reinforcing normative expectations about how voices correspond to gender [16].

A similar process occurs in computer vision systems that perform gender recognition from facial features. These systems rely on training data that often encode narrow and stereotypical representations of gender, leading to higher error rates for individuals who do not conform to these norms [3]. When integrated into interactive systems, these inferred classifications can influence downstream features such as avatar generation or identity representation, further reinforcing misclassification.

Language-based models also contribute to gender inference by associating names, professions, and linguistic patterns with gendered categories. These associations, learned from large-scale datasets, can influence generated text and automated decisions, reproducing stereotypical mappings even in the absence of explicit gender input [2,12].

Across these cases, gender is not required by the interaction structure but introduced through statistical inference. For users who rely on accessibility technologies as their primary interface, these inferred classifications become embedded in the interaction process, shaping how they are interpreted by systems without their direct control.

Combined Effects of Accessibility and AI on Gender

Accessibility technologies and AI-driven systems operate together within interaction processes, where accessibility mediates how input is captured and output is rendered, while AI systems interpret and transform this information. As a result, gender is shaped through the combined effects of structural constraints and probabilistic inference, as illustrated in Figure 1.

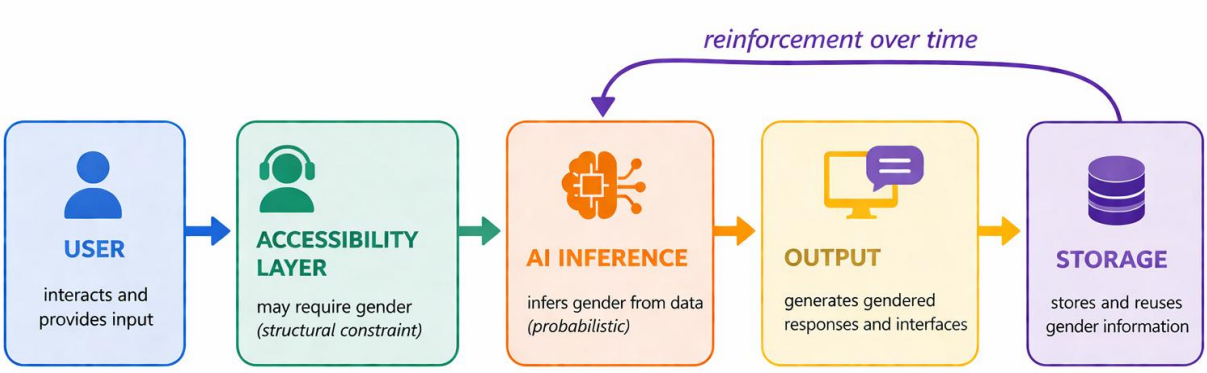


Figure 1: Accessibility and AI interaction reinforcing gender over time.

A key effect of this interaction is the stabilization of inferred gender as if it were explicitly provided by the user. Accessibility systems often require gendered output—for example, through grammatical agreement or identity fields—while AI systems supply gender classifications based on inferred signals such as voice or language use [16,2,12]. When these inferred values are used to fulfill structural requirements, they become embedded in system outputs and may subsequently be stored and reused across interactions. Prior work has shown that such classifications are often treated as stable attributes despite their uncertainty [7].

This interaction can be observed in accessibility-mediated voice interaction. A user relying on voice input—due to visual or motor impairments—interacts with a system that performs speech recognition and language processing. Based on vocal characteristics, the system infers a gender category, a process known to exhibit systematic disparities [16]. This classification may then be used in generated responses and realized through text-to-speech output, particularly in languages such as Portuguese, where grammatical gender must be expressed. If stored within system profiles or interaction histories, the same classification may be reused in future interactions, reinforcing the assigned gender over time.

Such feedback loops between inference, output, and reuse are characteristic of adaptive AI systems [11].

Similar dynamics can occur in assistive text-generation and augmentative and alternative communication (AAC) systems. These systems rely on predictive language models that encode gendered associations between names, roles, and expressions [2,12]. As users interact with these systems, suggested or generated content may introduce gendered language that does not reflect their intended identity, and these patterns can persist through personalization mechanisms.

More broadly, accessibility infrastructures shape the data that AI systems rely on. Interaction traces generated through accessibility tools—such as voice input, structured profiles, or simplified text—can encode constrained or inferred representations of gender. These representations may then be incorporated into adaptive system behavior, reinforcing bias over time [11,17].

The interaction between accessibility mechanisms and AI inference introduces practical challenges for system design. In accessibility-mediated contexts, gender may be required to produce system output while also being inferred from interaction data, leading to persistent assignments that are not explicitly defined by the user. Situations in which gender is absent, ambiguous, or incorrectly inferred raise questions about how such information should be handled and how users can intervene in system behavior. The following section examines these challenges from a design perspective.

Design Considerations for Gender in Accessible AI Systems

The analysis highlights several considerations for the design of systems in which accessibility and AI jointly shape how gender is represented during interaction. Rather than prescribing general solutions, the following points identify areas where current system behavior may introduce constraints or misrepresentation, based on the mechanisms discussed in the previous section.

Reduce reliance on mandatory gender categories

Accessibility mechanisms such as text-to-speech and structured profiles often require gendered representations even when no explicit information is provided. Supporting neutral or unspecified forms, particularly in languages with grammatical gender, can help avoid the imposition of binary assumptions.

Limit the role of inferred gender in system behavior

AI-driven classifications based on voice, language, or visual features may not reflect user identity and are frequently derived from incomplete or biased data. Restricting how such inferences are used - or avoiding their use when not strictly necessary - can reduce the impact of algorithmic misgendering.

Make gender-related system behavior visible and adjustable

When gender is inferred or propagated within a system, users may have limited awareness or control over how it affects interaction. Providing mechanisms to inspect, modify, or override gendered outputs is particularly important in accessibility contexts where interaction is mediated through automated processes.

Prevent persistence and propagation of inferred gender across interactions

As it was shown before, when coupling accessibility and AI, inferred gender may be stored and reused as if it were user-defined, reinforcing a particular classification over time. Designing systems to minimize unintended retention or cross-context reuse of such data can reduce long-term bias effects.

Consider accessibility data as part of AI bias pipelines

Interaction traces generated through accessibility tools—such as voice input or adaptive text systems—can influence model behavior and personalization. Auditing how such data is collected, interpreted, and reused is important for understanding how bias may be reinforced across system layers.

Conclusions

This paper examined how gender bias emerges through the interaction between accessibility technologies and AI-driven systems. By distinguishing between structural constraints in accessible interaction and probabilistic inference in AI systems, we showed how gender can be both required and inferred during use. The analysis highlights that bias arises not only from individual components, but from their combination, which can stabilize and propagate gender representations that do not reflect user identity.

The findings contribute a system-level perspective on gender in Human–Computer Interaction by framing accessibility as an interaction infrastructure and examining its coupling with AI inference. This perspective helps identify recurring mechanisms through which gender is introduced and reinforced in automated interaction, while also informing design considerations for more inclusive systems.

This work is limited by its qualitative and non-empirical scope, focusing on interaction patterns rather than measuring their prevalence or impact. It also does not include direct user participation. Future work can build on this analysis by incorporating empirical and participatory approaches to further examine how these mechanisms affect different user groups in practice.

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A Hybrid Technology-Assisted Social-Emotional Learning Model: Integrating Narrative Pedagogy and Digital Scaffolding for Students with Mild Intellectual Disabilities

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Abstract

This study develops an ecologically grounded instructional model integrating social-emotional learning (SEL) and literacy to support students with mild intellectual disabilities in authentic classroom contexts. Although SEL is widely recognized as essential for academic development, interpersonal competence, and well-being, persistent difficulties in emotional regulation, communication, and classroom engagement continue to constrain both social participation and learning outcomes. These challenges highlight the need for integrated, developmentally appropriate instructional approaches. Participants were 32 students in Grades 3–5 (ages 9–11) from 12 elementary schools in southern Taiwan. The study evaluates the Chinese Life Education Picture Storybooks (CLEPS) curriculum, a culturally responsive, picture storybook-based intervention designed to embed SEL within literacy instruction. A quasi-experimental one-group pretest–post-test design was employed to assess changes in students' learning outcomes, prioritizing ecological validity in naturalistic classroom settings.

Results demonstrated statistically significant improvements across all measured dimensions ($p < .05$), with large effect sizes ($\eta^2 > .14$), indicating substantial and educationally meaningful gains. These findings suggest that the CLEPS intervention effectively supports both social-emotional and literacy development. While causal inferences are limited by the study design, the results provide robust, practice-based evidence of instructional effectiveness in real-world contexts.

This study reconceptualizes instructional effectiveness as an ecologically situated process integrating social-emotional and cognitive learning in inclusive classrooms. By foregrounding ecological validity, it contributes to context-sensitive evaluation of educational interventions. Future research employing randomized controlled designs is recommended to strengthen causal inference and extend generalizability.

Introduction

Social-emotional learning (SEL) is strongly associated with academic achievement and interpersonal competence and has been widely recognized as a critical foundation for students' academic success, interpersonal development, and long-term well-being (Collaborative for Academic, Social, and Emotional Learning [2,5]. Core competencies [3,4] - including self-awareness, self-management, social awareness, relationship skills, and responsible decision-making - support meaningful participation in educational settings and are considered foundational for successful school engagement. Increasingly, research highlights the interconnected nature of social-emotional and cognitive development, suggesting that SEL is integral to, rather than separate from, academic learning. In particular, social-emotional competencies may serve as enabling conditions for literacy development through their influence on engagement, self-regulation, and meaning-making processes.

For students with mild intellectual disabilities, the development of SEL competencies is particularly critical, as these learners often encounter persistent challenges in emotional regulation, social communication, classroom engagement, and abstract reasoning [10,11]. These difficulties may hinder peer relationships and academic progress, especially in inclusive classroom environments. Without explicit and developmentally appropriate instruction, such challenges may persist and increase the risk of

adverse outcomes. Emerging evidence indicates that SEL competencies are teachable when instructional approaches align with learners' cognitive characteristics [7]. At the same time, narrative-based instructional approaches—particularly picture storybook reading—offer meaningful opportunities to integrate emotional and cognitive learning processes. Story-based learning environments support perspective taking, emotional reflection, and language development, thereby facilitating both social-emotional and literacy growth [1,9].

Recent research further suggests that SEL competencies are teachable when interventions align with learners' cognitive needs [7]. Evidence also indicates that SEL may positively influence literacy achievement by enhancing motivation, emotional regulation, and collaborative learning processes [8]. Narrative-based instructional approaches, including guided picture storybook reading, provide emotionally meaningful contexts that promote both language development and perspective taking [6]. Picture storybooks are widely used in elementary education and offer structured narrative contexts that support emotional understanding, perspective taking, and language development [1,9].

Existing research on SEL interventions can be broadly categorized into two dominant approaches. The first emphasizes narrative-based and teacher-mediated instruction, such as storybook reading and guided discussion, which provide contextualized, socially meaningful learning experiences. The second focuses on technology-assisted learning environments, including digital applications, multimedia systems, and interactive platforms, all designed to enhance accessibility and engagement.

Despite these advances, limited research has examined integrated instructional models that simultaneously address SEL and literacy development for students with mild intellectual disabilities. Moreover, there remains a need for empirically grounded evidence demonstrating how such approaches function in authentic classroom contexts, where instructional effectiveness must be evaluated in relation to ecological validity rather than strict experimental control.

Addressing this gap, the present study evaluates the Chinese Life Education Picture Storybooks (CLEPS) curriculum, a culturally responsive, picture storybook-based instructional program designed to integrate SEL and literacy learning. The CLEPS framework is distinctive in its explicit integration of affective and cognitive domains through structured narrative engagement. Situated within a naturalistic classroom context, this study aims to provide empirically grounded evidence of pedagogical effectiveness by examining changes in students' learning outcomes following the intervention.

Although both narrative-based and technology-assisted approaches have distinct strengths, they are often treated as separate paradigms. Narrative-based interventions may lack systematic scalability, while fully digital approaches may impose excessive cognitive demands on learners with intellectual disabilities, particularly when processing abstract emotional concepts. To address this gap, the present study proposes a hybrid instructional model that integrates narrative pedagogy with technology-assisted scaffolding. By combining culturally grounded picture storybooks, structured teacher-guided interaction, and digital visual supports, the CLEPS intervention seeks to provide an accessible and effective pathway for SEL development.

Our Work

Building on this literature, the present study evaluates the CLEPS curriculum, a culturally responsive picture storybook program designed to integrate SEL and literacy instruction for students with mild intellectual disabilities. This study examines both the effectiveness of this intervention and the mechanisms through which it supports learning.

Social-Emotional Learning and Students with Mild Intellectual Disabilities

SEL encompasses a set of competencies related to emotional understanding, self-regulation, and social interaction. Students with mild intellectual disabilities often demonstrate difficulties in adaptive

behavior, communication, and social interaction [10,11]. These challenges can affect both academic achievement and social integration, highlighting the importance of targeted instructional support. Students with mild intellectual disabilities often exhibit delays in these areas, which can affect both academic performance and social participation. Research emphasizes that explicit instruction, repeated practice, and contextualized learning are essential for supporting SEL development within this population.

Social-Emotional Learning and Academic Development

SEL has been linked to a range of positive academic and social outcomes. Emotional regulation and social competence contribute to students' engagement, motivation, and capacity to navigate learning environments effectively [2,5]. These competencies are especially important for students who face additional learning challenges.

Narrative-Based Learning and Literacy

Narrative-based approaches, including picture storybook reading, provide structured contexts for language development and emotional understanding. Shared reading practices have been shown to enhance both literacy and social-emotional competencies [1]. From a cognitive perspective, narratives support meaning-making processes essential for comprehension[9].

Technology-Assisted Learning in Special Education

Technology-assisted learning has been widely applied in special education to support accessibility, engagement, and individualized instruction. Digital tools such as tablets, multimedia presentations, and interactive systems can offer visual supports and repeated exposure, which are particularly beneficial for learners with cognitive challenges.

However, research also indicates that overly complex digital environments may increase cognitive load and reduce learning effectiveness.

Conceptual Framework

This study is grounded in an integrated theoretical framework (Figure 1 & Figure 2):

1. Cognitive Load Theory → Digital scaffolding reduces cognitive burden.
2. Sociocultural Theory → Teacher-guided interaction mediates learning.
3. Multimodal Learning → Visual + verbal inputs enhance comprehension.

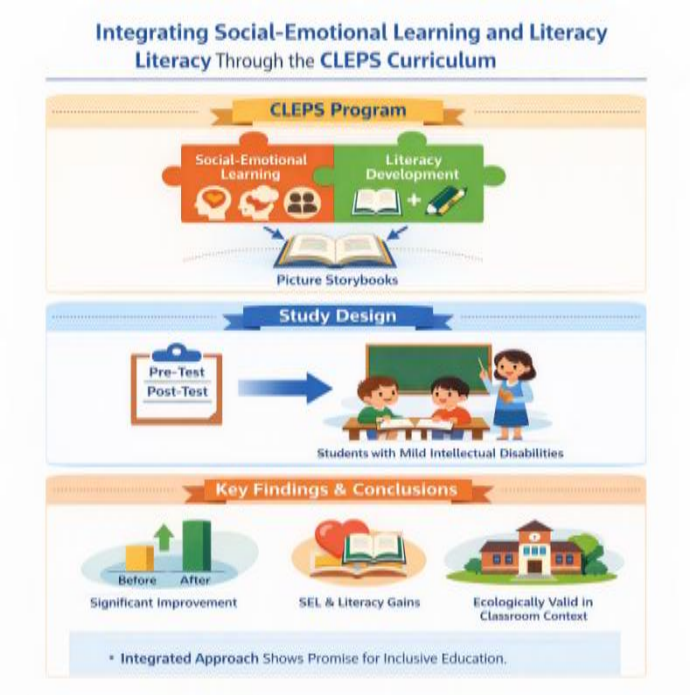


Figure 1: Integrating SEL and Literacy through the CLEPS Curriculum

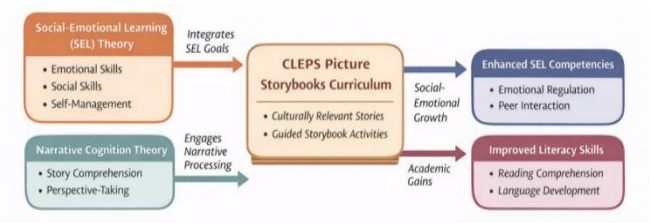


Figure 2: CLEPS Intervention Theoretical Framework

Research Gap and Contribution

While both narrative-based and technology-assisted approaches have demonstrated effectiveness, few studies have examined how these methods can be **systematically integrated**. This study addresses this gap by proposing a hybrid model that combines narrative context, teacher-guided interaction, and digital scaffolding. Although previous research emphasizes the importance of SEL and literacy, there is limited investigation into integrated instructional approaches within ecologically valid classroom contexts. The present study evaluates a combined SEL–literacy model to advance this area of inquiry.

Methodology

Research Design

This study adopts a quasi-experimental one-group pretest–post test design to examine the effectiveness of the CLEPS intervention. This approach prioritizes ecological validity and enables the investigation of instructional effectiveness within authentic classroom settings. It represents a deliberate methodological choice to capture the complexity of instructional processes in real educational environments, where random assignment and the use of a control group are not feasible due to ethical and practical constraints.

Participants

A total of 32 elementary school students, enrolled in Grades 3–5 (ages 9–11) across 12 schools in southern Taiwan participated in the study. The sample included 19 boys and 13 girls. Participants were formally identified as having **mild intellectual disabilities**, with some also presenting co-occurring learning disabilities or social-emotional and behavioral difficulties, as determined by school-based assessment procedures. This heterogeneity reflects the diversity commonly found in inclusive educational settings. In addition, 16 teachers were involved in implementing the intervention and evaluating student performance, reinforcing ecological validity in real classroom contexts. All participants and their parents provided informed consent prior to participation.

Instruments

Four instruments were used to evaluate the outcomes of the CLEPS intervention. The Literacy Learning Scale (LLS), completed by teachers, assessed students' literacy performance before and after each CLEPS unit. The Social-Emotional Learning Skill Scale (SELSS) was administered in both teacher-report and student self-report forms to measure core SEL competencies. The Mood Thermometer Survey Scale and the Zodiac Survey Scale were completed by students to capture self-perceived emotional reactions and social-emotional behaviors. All instruments demonstrated acceptable reliability for the study population. As indicated in Table 1, teachers implemented structured lessons using five Chinese Life Education Picture Storybooks (CLEPS) that integrated culturally relevant narratives with explicit SEL instruction. Literacy and SEL outcomes were assessed using teacher and student ratings before and after the program.

Intervention: Development of the CLEPS Curriculum

The CLEPS curriculum is a culturally responsive instructional framework integrating social-emotional learning and literacy through guided picture storybook engagement. The program emphasizes structured narrative interaction, emotional reflection, and language development, allowing for the simultaneous cultivation of affective and cognitive competencies (Table 1 & Figures 1–3). Figure 1 illustrates the integration of SEL and literacy through the CLEPS curriculum, Figure 2 presents the theoretical framework of the CLEPS intervention, and Figure 3 depicts the conceptual model of the hybrid technology-assisted SEL framework.



Figure 3: Conceptual Model of the Hybrid Technology-Assisted SEL Framework

Table 1: Content of the Five CLEPS and Teaching Objectives

CLEPS Name	Main Story Content	Teaching Goals
 Lying Shepherd Boy	Honesty is the best policy. People must learn from their mistakes. Lying to oneself or others leads to mistrust and a lack of respect for oneself and others. Fooling others leads to fooling oneself.	1. Self-Awareness 2. Self-Management 3. Social Awareness 4. Social Management
 Trick or Treat Old Man	Violence does not solve problems or challenges. Less labelling and more love for that certain someone around us. Replacing one tyranny with another cannot establish exemplary relationships. Overcome all struggles or difficulties with wisdom or effective SEL skills.	1. Self- Awareness 2. Self-Management 3. Social Awareness 4. Social Management
 Little Life Fighter	Li Zhenqi suffered from Aplastic Anemia (AA) and was nicknamed "Big head with incredible ideas." His sister donated Human Leukocyte Antigen (HLA) to save his life. Life is hard-won. Learn to cherish it. Life is fragile, so we should cherish it and welcome happiness. Communication is the best problem-solving strategy, and loving is the best way to overcome various difficulties.	1. Self-Awareness 2. Self-Management 3. Social Awareness 4. Social Management
 Gorilla	Anna loved gorillas passionately and wished her father could take her to see an actual gorilla in the zoo. Her hard-working and busy father couldn't spend time with her. The main topic of this story is the parent–child relationship and single-parenting in contemporary society.	1. Self-Awareness 2. Self-Management 3. Social Awareness 4. Social Management
 I Still Have One Leg	Zhou Da-Guan, a person with a single limb difference (one leg), aspires to bring happiness to people around the world. Inspiring figures include Zhen Fen-X, a person with a physical disability, Helen Keller, a person who was blind and deaf, and Beethoven, a person who was deaf. Learning to respect and honor the experiences of people with disabilities or differences is essential. Always bear in mind the following virtues (heart of gratitude): understanding, forgiveness, gratitude, contentment, and blessings. Altruistic feedback and contributing to others' well-being.	1. Self-Awareness 2. Self-Management 3. Social Awareness 4. Social Management

Note. Permission for the use of CLEPS images was granted by Windmill, Fu-Di.

Conceptual Framework

The curriculum was developed based on the five core SEL competencies: self-awareness, self-management, social awareness, relationship skills, and responsible decision-making. These competencies guided both the selection of instructional materials and the design of learning activities.

Selection of Picture Storybooks

Five picture storybooks were selected according to the following criteria: a) alignment with SEL learning objectives; b) cultural relevance to students' lived experiences; c) clarity of narrative structure and emotional content; and d) potential to stimulate discussion and reflection. This process ensured that the materials were pedagogically meaningful and contextually appropriate.

Design of Instructional Components

The CLEPS curriculum integrates three key instructional components:

- Narrative-based learning: Storybooks serve as the foundation for introducing emotional and social situations, enabling students to explore characters' perspectives and experiences.
- Guided discussion and reflection: Teachers facilitate structured discussions to help students identify emotions, interpret social interactions, and connect the stories to their own experiences.
- Technology-assisted instructional design / visual scaffolding: To enhance comprehension, key SEL concepts are transformed into digital visual-text cards that reinforce abstract ideas through simplified language and illustrations. These materials were digitized and presented via tablets (e.g., iPads) and interactive whiteboards. Teachers used these digital supports to highlight key concepts, provide step-by-step explanations, and facilitate repeated exposure. This hybrid approach enhances comprehension by reducing cognitive load and supporting multimodal learning while maintaining the benefits of teacher-guided interaction.

Teacher Involvement

Teachers played an essential role in implementing and refining the CLEPS curriculum. They reviewed instructional materials, adapted teaching strategies to student needs, facilitated discussions, guided learning activities, and provided evaluative feedback on student progress. This collaborative approach ensured that the curriculum remained both **practical and responsive to classroom realities**.

Positioning within Technology-Assisted Learning

Although CLEPS is grounded in traditional storybook instruction, its integration of digital presentation tools positions it as a **hybrid, technology-assisted intervention**.

Unlike fully digital systems, CLEPS emphasizes teacher-guided interaction, structured emotional scaffolding, and multimodal learning support. This approach is particularly effective for students with mild intellectual disabilities, who often benefit from **human mediation combined with visual digital aids**.

Intervention Procedure

Sixteen special education teachers participated in a two-day training workshop focused on implementing the CLEPS curriculum and related instructional strategies. The intervention included five CLEPS titles delivered across 12 weeks, with two 40-minute sessions per week. Instruction emphasized explicit modeling, guided discussion, peer interaction, and reflective activities aligned with SEL objectives. Teachers followed standardized lesson plans to ensure instructional consistency across schools.

Each session followed a consistent instructional sequence (Figure 1):

- Guided reading of a picture storybook
- Teacher-led discussion of emotional and social themes
- Reflection activities to support comprehension
- Reinforcement of key SEL concepts

Data Collection and Data Analysis

Pretest and post-test measures were administered to assess changes across the CLEPS dimensions. Paired comparison analyses were conducted to examine differences between pre-intervention and post-intervention performance, and effect sizes (η^2) were calculated to evaluate the magnitude of observed changes. Descriptive and inferential analyses included one-sample t-tests, paired-samples t-tests, and repeated-measures ANOVA. The t-tests were used to determine whether students' post-test scores on the LLS differed from their pretest results. Preliminary analyses were performed to evaluate homogeneity and assess correlations between teacher and student ratings of literacy learning, SEL skills, behavioral problems, and motivation. According to Cohen (1988), $\eta 2 = 0.01$ indicates a small effect, $\eta 2 = 0.06$ a medium effect, and $\eta 2 = 0.15$ a large effect size.

Paired-samples t-tests revealed significant improvements in students' literacy learning following each CLEPS unit, with post-test scores consistently exceeding pretest scores on the LLS. Large effect sizes were observed across all five CLEPS interventions (Table 1). Analyses of SELSS data indicated significant post-intervention gains in self-awareness, self-management, social awareness, and social management. Collectively, the results demonstrate that the CLEPS curriculum positively influenced both literacy and social-emotional learning outcomes, with significant improvements and strong agreement between teacher and student evaluations.

Paired comparison analyses revealed statistically significant differences between pretest and post-test scores across all measured dimensions. Participants demonstrated consistent improvements following implementation of the CLEPS curriculum.

As shown in Table 2, post-test scores were higher than pretest scores for each dimension, supported by large effect sizes (η^2). These results suggest substantial and educationally meaningful gains within the classroom context. Paired-samples t-tests indicated significant improvements in LLS scores across all five CLEPS units (all $p < .01$), with post-test performance consistently higher than pretest levels. Effect sizes, calculated using eta squared ($\eta^2 = t^2 / [t^2 + df]$), ranged from .94 to 99, indicating large to very large intervention effects. The CLEPS intervention, implemented through structured and individualized instructional strategies, substantially enhanced participants' literacy and social-emotional learning outcomes.

Table 2: Means, Standard Deviations, η2 and p Values of Students' Pretest and Post-Test - Scores on the Literacy Learning Scale

Variable	Description in details									
	Pretest		Post-Test							
No.	M	SD	M	SD	η^2	p	correlation	t	F	df
CLEPS-1	53.03	21.91	63.19	22.02	.98	<.01	.89	-5.56	10.29	31
CLEPS-2	57.14	20.40	66.75	21.06	.99	<.01	.90	-5.60	9.98	31
CLEPS-3	58.34	18.12	74.44	18.55	.94	<.01	.81	-8.05	4.48	31
CLEPS-4	53.72	19.70	69.52	18.28	.95	<.01	.85	-8.40	5.27	31
CLEPS-5	57.31	15.68	73.13	14.03	.96	<.01	.92	-14.72	9.61	31

Discussion

This study provides empirically grounded evidence of pedagogical effectiveness in authentic classroom settings. Statistically significant improvements were observed across all CLEPS dimensions, with large effect sizes indicating that the intervention produced educationally meaningful changes in students' learning outcomes. Improvements may reflect the potential value of integrating SEL and literacy through narrative-based instruction within real educational environments.From a methodological standpoint, the quasi-experimental one-group pretest–post-test design was a deliberate choice to prioritize ecological validity and capture instructional practices as enacted in authentic, inclusive classroom contexts, where experimental control is constrained. Instructional effectiveness is thus conceptualized as a contextually situated phenomenon rather than a purely causal outcome.

Overall, this study contributes to the growing body of research emphasizing ecological validity as a central consideration in evaluating instructional effectiveness. The results highlight the potential of integrated SEL and literacy approaches in inclusive education and suggest that **technology-assisted, narrative-based instruction can meaningfully enhance learning outcomes**. Future research employing randomized controlled designs is recommended to examine causal relationships and extend generalizability.

Theoretically, the study advances a **hybrid model of technology-assisted social-emotional learning**, where digital tools act as cognitive and mediational scaffolds within teacher-guided instruction. It extends existing findings by demonstrating that technological effectiveness in special education depends not on complexity, but on alignment with pedagogical and cognitive principles.

Conclusions and Possible Next Steps

This study provides empirically grounded evidence supporting the integration of social-emotional learning and literacy instruction in inclusive classrooms. The CLEPS curriculum demonstrates potential as an instructional model that promotes both affective and cognitive development. By foregrounding ecological validity, the study contributes to a more contextually grounded understanding of instructional effectiveness and underscores the importance of integrated pedagogical approaches for diverse learners.

Several limitations should be noted. The absence of a control group precludes definitive causal inference; alternative explanations, such as maturation, contextual effects, or increased assessment familiarity, cannot be fully ruled out. Nonetheless, consistent pre–post improvements and large effect sizes across multiple domains support the robustness of the findings. The study's sample was limited to students with mild intellectual disabilities, and the results should therefore be understood within this specific context. Future research involving larger, more diverse samples and controlled or comparative designs is encouraged to further examine causal relationships and extend generalizability.

Despite these limitations, this study contributes to the growing body of research emphasizing the alignment of methodological approaches with real-world educational practice. By integrating SEL and literacy instruction through a structured, narrative-based framework enhanced by technology-assisted scaffolding, the CLEPS curriculum offers a contextually responsive model that supports both affective and cognitive growth. Situated within a broader epistemological orientation that values ecological validity and context-sensitive inquiry over strict experimental control, this study views instructional effectiveness as an emergent, socially mediated process shaped by interaction among learners, pedagogy, and context. The consistency and magnitude of improvements across domains lend credibility to the robustness of these findings.

Finally, by focusing on students with mild intellectual disabilities, the study highlights the importance of designing interventions responsive to diverse cognitive and developmental profiles. The CLEPS framework, explicitly integrating social-emotional and literacy dimensions through narrative engagement,

provides a theoretically informed model for inclusive education. The findings reaffirm that technology-assisted learning in special education is most effective when pedagogical, cognitive, and design principles are coherently aligned.

In sum, this research contributes to an emerging understanding of instructional effectiveness as a contextually situated and ecologically embedded phenomenon. It underscores the need for future inquiry that balances ecological relevance with experimental rigor to clarify the conditions under which integrated SEL and literacy interventions are most effective.

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Augmentative & Alternative Communication Innovations in Products and Services

Development of an AI-Powered Assessment Tool for Communication Support for Children with Severe and Multiple Disabilities

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Abstract

With advances in medical technology, the number of children with severe communication disabilities has been rapidly increasing. There are growing numbers of cases in which children have no speech and it is difficult to interpret even basic intentions such as yes/no responses or preferences. In order to elicit intentional responses from these children, it is essential to understand their motor and cognitive abilities and to provide effective interventions appropriate to each child's developmental stage. In this study, an AI-powered application called TEAK was developed. The application automatically presents visual, auditory, and tactile stimuli while observing changes in the responses of children with severe and multiple disabilities. TEAK recognizes facial and body movements in order to visualize and analyze their motor and cognitive abilities. The usefulness of this application for communication support was also examined.

Introduction

Advances in medical technology have enabled children who previously had difficulty surviving to live longer lives, leading to a global trend toward increased severity and multiplicity of disabilities. The number of children requiring medical care has been increasing rapidly, particularly in developed countries, and many of these children experience significant communication difficulties. In the growing number of cases in which no clear responses can be observed, the use of conventional Augmentative and Alternative Communication (AAC) methods is often challenging [1]. Among the new AAC technologies expected to be useful for people with severe communication difficulties are alternative input devices based on eye-tracking [2] and devices that apply AI technologies such as large language models to help generate utterances efficiently [3]. However, for the children with severe and multiple disabilities discussed in this study, limitations in cognition and motor function make it difficult for them to understand and operate such input-support devices in the first place.

To support the development of children's communication abilities, namely their ability to interact with others, it is important to provide effective interventions tailored to each child. To this end, it is necessary to objectively assess each child's motor and cognitive abilities [4]. However, there are large differences in how the child's responses are interpreted, and subjective judgments are often involved. AI can be utilized to objectively grasp the actual state of children's cognitive and motor skills.

Various scientific approaches have been attempted to objectively capture their cognitive skills. For example, studies have used near-infrared spectroscopy (NIRS) to measure residual functions based on response characteristics in language-related brain regions [5], and others have examined ways of interacting with children with severe and multiple disabilities by using physiological indicators such as heart rate [6]. Additionally, there are studies that attempt to read intentions from brainwaves in individuals with severe disabilities who do not have intellectual impairments but are unable to speak [7]. However,

using these physiological data in everyday settings for communication support poses challenges, including their specialized nature and difficulties in achieving sufficient accuracy.

In contrast, this study examined methods of supporting communication that can be practiced routinely by anyone in schools and at home using readily available devices such as tablets and smartphones. Specifically, as an approach based on scientific evidence through automated observation, this study developed a new AI-powered application, TEAK, which automatically presents visual, auditory, and tactile stimuli while observing changes in the responses of children with severe and multiple disabilities. The application recognizes facial and body movements to visualize and analyze their motor and cognitive abilities.

Key functions of TEAK

TEAK consists of two main functions:

- Observation function: Using IoT (Internet of Things) technology, visual, auditory, and tactile stimuli are presented while recording the responses of a child with severe and multiple disabilities.
- Analysis function: The recorded video is processed using image-processing and AI-based body-part tracking technology to detect movements of the mouth, eyes, and face, which are then displayed in graph form.

The TEAK interface is shown in Figures 1 and 2. In the observation function shown in Figure 1, users can select the type of stimulation from the "Stimulus" menu in the center of the screen and set the duration and number of repetitions in the "Time/Repeat" fields. By pressing the "Obs(ervation) Start" button, the stimulus is automatically presented for the specified duration and number of repetitions, while the subject's responses are recorded simultaneously.

In the analysis function shown in Figure 2, the AI tracks the movements of the child's mouth, eyes, and face in recorded video, and the amount of movement is displayed on a graph. To identify the positions of each body part, this study adopted the Face/Body recognition model included in the Vision Framework of iOS and iPadOS. By comparing differences in responses (movements) to each stimulus, supporters can evaluate the child's motor and cognitive abilities.



Figure 1: Observation function of TEAK.

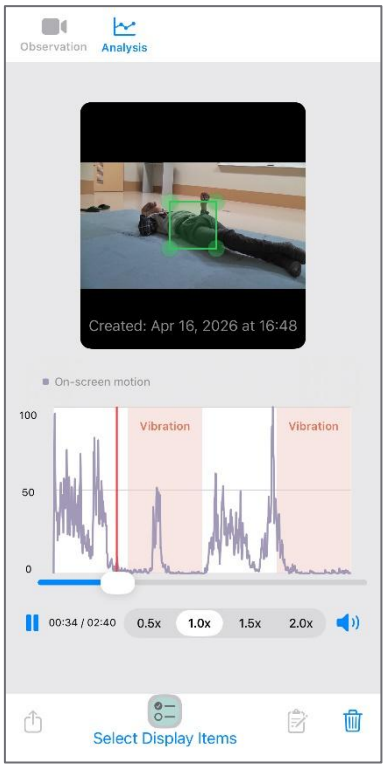


Figure 2: Analysis function of TEAK.

Methods

Two children with severe and multiple disabilities who have difficulty speaking (Case 1 and Case 2) participated in the experiment. Cases involving children with severe and multiple disabilities who have difficulty communicating can generally be divided into two types: (1) cases where spontaneous movements are present but their meaning is unclear, and (2) cases where movements are minimal and the child appears to show no response even when prompted. The two participants in this experiment each exhibited typical behaviors corresponding to these two categories and were designated as Case 1 and Case 2.

Case 1 was a non-speaking 12-year-old boy with cerebral palsy (CP) and profound intellectual disability. Regardless of the timing or presence of interaction, he frequently engaged in self-stimulatory behaviors such as rocking his body and touching his lips, making it difficult to understand the extent of his interest in the external environment or what he was perceiving. Therefore, we examined the presentation of tactile stimuli, which were expected to be easier for him to understand from a developmental perspective. Specifically, a device previously developed by our research team—the Visualizing Vibrator (VV) [8], which delivers vibrations via Bluetooth remote control—was attached with medical double-sided tape to four locations on his body: the shoulders, left hand, right hand, and back. For each of these four body areas, a no-vibration condition (A) and a vibration condition (B) were alternated, with each condition lasting 40 seconds, in an ABAB sequence while observations were conducted. Subsequently, changes in the child's overall body movements were analyzed using TEAK. Figure 2 above shows the analysis process for this Case 1 child.

Case 2 was a non-speaking 7-year-old boy with profound paralysis and intellectual disability due to myotubular myopathy. No substantial success had previously been achieved in communicating with the boy, and there were no distinctive responses associated with specific situations. Although the boy exhibited subtle, repetitive facial movements, it was unclear whether these movements were voluntary. His visual and auditory abilities were considered unmeasurable by his physician. For this child,

observations were conducted using an ABA design with alternating conditions: condition A (no music) for 30 seconds and condition B (with music) for 60 seconds.

Results and Discussion

Figure 3 shows the analysis results when vibration stimuli were applied to the right hand of the child in Case 1. The figure indicates that the child's body movements decreased when the vibration stimulus was present. This tendency for reduced body movement during vibration was observed not only when the right hand was stimulated, but also when stimuli were applied to the shoulders, left hand, and back. One possible explanation for the decrease in body movement is that the child's attention was directed toward the vibration stimulus. Going forward, as an approach to reducing his self-stimulatory behaviors and fostering engagement with others, it is desirable to present tactile stimuli, such as vibration, to these four body areas.

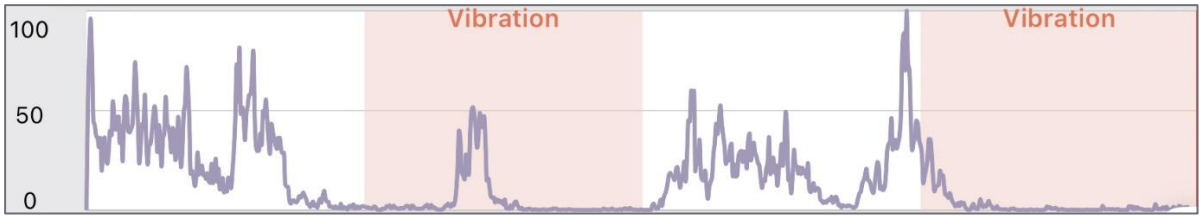


Figure 3: Changes in body movements of the Case 1 child with and without vibration.

Figure 4 shows the results of analyzing the magnitude of the child's facial movements in Case 2. The results indicate that the boy's subtle repetitive facial movements stopped approximately 5 seconds after music was played and resumed about 20 seconds after the music stopped. When this observation was repeated multiple times, similar results were consistently obtained, with facial movements decreasing during music playback.

These findings indicate that the child showed stimulus-contingent changes in movement in response to music (i.e., self-stimulatory movements stopped when music was played), suggesting that he was able to hear the sound and that his attention was directed toward it. It was also found that his responses to sound were delayed by approximately 5–20 seconds. Based on these findings, guidance for communication support was obtained, indicating that interactions using sound are possible with this child by patiently waiting for his responses.

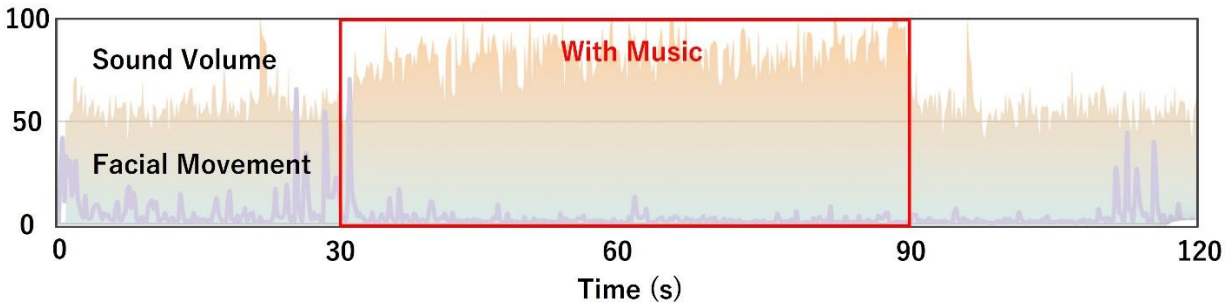


Figure 4: Changes in facial movements of the Case 2 child with and without music.

Conclusions

In this study, an AI-powered application, TEAK, was developed to support the assessment of motor and cognitive abilities in children with severe and multiple disabilities, and its effectiveness for communication support was investigated. In the experiment involving two children with severe and multiple disabilities using the developed application, it was possible to capture changes in body and facial movements associated with stimuli that indicate more effective approaches for supporting communication.

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Blindness, Low Vision: New Approaches to Artwork Perception and ICT Mediation

Beyond the Visible: Multimodal Digital Game in Collaboration with Polish Association of the Blind

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Abstract

The global video game industry is growing rapidly, yet accessibility for blind and low vision (BLV) players remains limited. This study aims to identify key barriers and design solutions to create engaging and inclusive gaming experiences for BLV individuals. A user-centered design approach is employed, combining literature review, in-depth interviews with BLV participants, and prototyping of an accessible game. The resulting guidelines and prototype will provide practical recommendations for developers to improve non-visual game interaction and overall accessibility, fostering inclusive gameplay experiences.

Introduction

The global video game market has been growing steadily, with increases observed not only in the number of players but also in industry revenues. This growth is evident across all major market segments, including gaming consoles, personal computers, and mobile devices, as well as across different geographic regions [1].

In the context of this continuous industry expansion, it is important to draw attention to user groups that may be overlooked or insufficiently considered in the game design process, such as people with disabilities. This paper focuses specifically on one such group: blind and low-vision (BLV) individuals.

The objective of this study is to identify design recommendations for accessible gaming experiences for BLV players. The findings are used to inform the design of a game prototype that supports full accessibility for BLV users. The prototype is then evaluated in order to assess the applicability of the proposed recommendations.

State of the Art

Related Work

Despite the scale of the modern gaming industry, the proliferation of non-visual games, and the increasing engagement of BLV players, their gaming experiences remain understudied. There is a notable lack of specific studies focused on designing tailored experiences for BLV players. Despite some game developers' attempts at increasing accessibility, many BLV individuals choose to abandon gaming altogether [2]. BLV gamers display similar preferences to most other gamers, and despite great potential for improvement, there persists a significant gap in accessibility for BLV individuals interested in digital games [3]. Some researchers point to audio description as an underutilized tool that could help bridge that gap [4].

According to the findings of the industry consultations described in the Accessible Gaming Research Report (2022), BLV individuals continue to report significant challenges in discovering and playing video games, even when utilizing dedicated plugins or specialized systems designed to meet their requirements. Furthermore, although game developers increasingly incorporate accessibility features into their projects, they rarely display full understanding of the specific needs of BLV gamers [5].

Video Game Accessibility

Accessibility in the context of digital product design refers to creating solutions that can be used by as many people as possible, regardless of their physical, sensory, or cognitive limitations. This definition does not apply exclusively to people with disabilities, but also to users who, due to their age, temporary limitations, or environmental conditions, may encounter difficulties when using digital products [6]. In recent years, globally recognized game developers, such as Naughty Dog and Santa Monica Studio, have started implementing accessibility features in their titles [7]. For instance, The Last of Us received a remake featuring a wide range of accessibility options [8].

When designing an accessible game, a developer needs to take into consideration factors such as potential types of disability (visual, hearing, motor, cognitive), and specific game elements that in their case may require more careful attention (e. g. screen design, navigation, multimedia content, language) [9] [10]. According to Yuan et al. [9], accessibility barriers for players with diverse abilities can occur at three different stages of player interaction: receiving stimuli, determining a response, and providing input.

For BLV players, accessibility challenges are particularly significant, as most video games rely heavily on visual information. Limitations in perceiving visual stimuli can prevent access to essential gameplay cues, which in turn affects decision-making and the ability to provide effective input. This interdependence highlights that accessibility requires a holistic approach to game design that incorporates alternative channels of information delivery, such as audio or haptic feedback, throughout the gameplay experience [5].

The Accessible Gaming Research Report from 2022 [5] indicates that BLV gamers desire access to all types of games and the agency to select specific genres of their choosing. At the same time, the report identifies accessibility as the primary barrier preventing BLV individuals from engaging in video games or leading them to abandon gaming altogether. BLV ex-gamers and non-gamers frequently cite insufficient accessibility features as key reasons for disengagement. Furthermore, accessibility issues are reported across nearly all game genres, including shooters, adventure games and role-playing games, both single- and multiplayer, suggesting that these barriers are systemic rather than genre-specific. Even players who continue to play games often do so despite persistent accessibility challenges.

However, the report indicates that not all game genres present the same level of accessibility challenges for BLV players. Audio games are among the genres with the fewest reported accessibility issues, with only around 8% of the overall BLV sample indicating difficulties. As a particularly inclusive genre, audio games illustrate the potential of non-visual game design to provide more inclusive gameplay experiences and better accommodate the interaction needs of players with vision impairments.

Market solutions for BLV Gamers

The Accessible Gaming Research Report [5] highlights several games that, according to interviews with BLV gamers, offer sufficient accessibility features. These include *Halo Infinite*, *Forza Horizon 5*, *Far Cry 6*, and *The Last of Us Part II*. These games include features such as customizable, scalable UI and subtitles, high contrast modes, systems of additional markers and wayfinding options, which makes them especially suited for players with some residual vision, as they greatly enhance their ability to use the existing visual interfaces of the game. Some provide additional features such as audio description, text-to-speech, audio cues, and navigation/driving assists that make them fully playable for players with no vision [8, 11, 12]. Games accessible to blind gamers also include most text-based and logic games that don't require fast reaction times and can be compatible with a screen reader. Audio games mentioned in the AGR Report, which are designed to be played only using sound-based interfaces, include *A Blind Legend*, *Knight-Manager*, and *The Vale: Shadow of the Crown* [5]. The latter is a particularly promising example of collaboration between game developers and the blind community, as it was developed with

the help of the Canadian National Institute for the Blind [13], and has accumulated more than 300 player reviews on Steam, 97 percent of which are positive [14].

Methodology

Research Design

The research followed a qualitative, user-centered design approach structured into two main phases: an exploratory phase and an evaluative phase.

The exploratory phase consisted of in-depth interviews (IDI) with BLV participants to identify key barriers, needs, and strategies related to digital game accessibility.

The evaluative phase involved the development of a functional game prototype and its usability evaluation with both BLV and sighted users. The evaluation was conducted through a structured gameplay session within a single demo scene incorporating multiple interaction types, combined with post-study questionnaires.

This structure allowed for a direct connection between user needs and design decisions, ensuring that the proposed solution is grounded in empirical findings rather than assumptions.

Exploratory Study – In-depth Interviews

The study involved 14 visually impaired participants aged 18–45, including 9 blind and 5 low-vision individuals, all with prior experience in digital gaming. Participants were recruited partly in collaboration with the Polish Association of the Blind.

Data was collected through semi-structured interviews focusing on experiences with digital games, perceived accessibility barriers, and factors supporting gameplay.

The interview protocol covered three main areas: (1) gaming experience (types of games, frequency, preferences), (2) accessibility barriers (e.g., interface design, accessibility features, interaction constraints), and (3) enabling factors (e.g., screen reader compatibility, audio design, navigation, and control schemes). Participants were also asked to identify gaps in the current game market and unmet accessibility needs.

Data Analysis (IDI)

Data from the in-depth interviews were analyzed using thematic analysis. The analysis followed an inductive approach, focusing on identifying recurring patterns related to accessibility barriers, enabling factors, and gameplay experiences of BLV participants.

Interview transcripts were coded and grouped into higher-level themes corresponding to key areas of interest: (1) barriers in digital games, (2) accessibility features and gameplay solutions, and (3) unmet needs and common gaps in game design. These themes were then used to extract actionable insights for the design of the game prototype.

Prototype Development

The game prototype was designed primarily with BLV users in mind, adopting a multimodal approach with a strong focus on audio-based interaction, where 3D spatial audio served as the primary channel for navigation, interaction, and narrative delivery. The prototype consisted of a fully voiced narrative scene interspersed with a number of short gameplay sequences, each revolving around different ways of interacting with an audio interface, utilizing either the computer keyboard or the mouse. These included spatial navigation using 3D audio, interpreting audio cues to infer information about the environment, and a rhythm-based challenge. While prioritizing BLV accessibility, the sound design was

intended to support a universal, engaging experience for all users. The game did not use audio description; instead, all narrative and gameplay information was conveyed through an in-game narrator and integrated audio cues.

Usability Testing

The final phase involved preliminary usability testing of the game prototype with three participants, including one blind and two sighted users, as an initial evaluation of the inclusive design approach.

The evaluation was conducted through a task-based gameplay session using a single demo scene with multiple interaction types. Participants completed gameplay tasks while providing concurrent think-aloud feedback, enabling identification of initial usability issues related to navigation, interaction, and audio-spatial cues.

Following the session, participants completed the Post-Study System Usability Questionnaire (PSSUQ) to assess perceived usability, interface quality, and overall user satisfaction.

Results

Exploratory Study (IDI)

Participants' Gaming Experience and Attitudes

Gaming engagement varied depending on the degree of visual impairment. Blind participants reported lower gameplay frequency and more restricted game selection, typically limited to highly accessible formats such as quiz-based, puzzle, card or simple mini-games. Low-vision participants demonstrated broader engagement, including mainstream titles across multiple genres and platforms.

Multiplayer gameplay emerged as a central aspect of the gaming experience across the sample. Online and cooperative modes were valued for their social dimension, interaction with other players, and sense of community. Independence and equal participation were consistently emphasized, with particular importance placed on the ability to play without assistance and to compete on equal terms with sighted players.

Accessibility Needs in Digital Games

Accessibility was identified as a prerequisite for meaningful gameplay. The most critical requirement was full screen reader compatibility, including semantically meaningful and properly labeled interface elements enabling reliable navigation of menus and in-game systems. Inadequate UI labeling or inconsistent screen reader output was reported to severely limit or prevent gameplay.

Audio design played a dual role. Consistent and meaningful audio feedback supported navigation, orientation, interaction, and decision-making, while poorly structured soundscapes led to auditory overload caused by overlapping effects, background audio, and competing interface cues, significantly increasing cognitive load.

For low-vision participants, key requirements included UI scaling, contrast adjustment, and dark mode support, all of which reduced visual strain and improved readability. The use of color differentiation (e.g., color-coded dialogue or interface elements) was also highlighted as supporting content distinction and improving overall clarity. Interface adaptability and the visibility of critical gameplay elements were essential for usability in mainstream titles.

Across all interviews, participants stressed that accessibility must be embedded in core game design rather than implemented as an optional layer. Partial or inconsistent accessibility implementations frequently resulted in restricted progression or complete inability to continue gameplay.

Systemic Barriers and Role of Community

Barriers to independent gameplay were linked to systemic issues in game development, including lack of standardized accessibility practices, limited inclusion of BLV users in design processes, and inconsistent implementation across titles.

Participants described extensive compensatory strategies, including memorization of interface structures, trial-and-error navigation, and reliance on incomplete audio cues for state interpretation. Beyond in-game adaptation, external intervention was often necessary to enable playability.

High technical competence was frequently required, including use of modifications, screen reader extensions, translation plugins, and other third-party tools. In many cases, gameplay depended more on user-driven adaptation than on built-in accessibility features.

The gaming community played a significant enabling role by providing shared knowledge, tutorials, and technical guidance, including modding, partially compensating for insufficient developer support. It also functioned as a key source of information about accessible titles, without which some participants would have limited awareness of available games.

Overall, gameplay accessibility was shaped by an ecosystem in which gaps in design are addressed through user effort, external tools, and community support rather than standardized industry practices.

Market Gaps and Missing Accessibility Solutions

A key gap identified was the lack of systematic consideration of accessibility in early stages of game development, resulting in partial or missing accessibility in otherwise complex and high-quality titles.

Participants reported limited diversity of accessible games, typically restricted to quiz apps or casual audio games. These games were often perceived as lacking depth and characterized by repetitive mechanics, leading to reduced long-term engagement and a sense of infantilization. In contrast, mainstream games offer greater genre diversity, richer mechanics, and more complex narratives, but remain largely inaccessible despite participants' interest in engaging with them.

Importantly, some participants noted that in certain cases, relatively minor design changes—such as the addition of structured audio cues or more comprehensive audio feedback—could significantly improve accessibility of otherwise inaccessible titles.

A significant and repeatedly mentioned barrier was the absence of Polish language support, which frequently led to abandoning otherwise accessible or appealing titles due to reduced comprehensibility of narrative and interface content.

Additional barriers included inconsistent accessibility implementation across updates and insufficient integration of accessibility features into core gameplay systems. Accessibility was viewed as insufficient when not combined with gameplay depth, narrative engagement, and replayability.

Overall, findings indicate a structural mismatch between accessibility and engagement: accessible games often lack depth, while engaging mainstream games remain largely inaccessible to BLV players.

Usability Testing

During the preliminary testing of the prototype, players expressed a general satisfaction with the gaming experience. The narrative and implemented mechanics were evaluated positively by all participants and were equally understandable and engaging for the sighted as well as the blind tester. The use of realistic audio cues in mini-games was particularly appreciated, as it enhanced spatial understanding and supported navigation without the need for visual information or audio description. The absence of audio description was not perceived as a limitation by the blind participant, and the design successfully used integrated interactive audio to provide all necessary information about the game's environment.

The sighted participants reported greater difficulty in paying attention to audio instructions and rated the interface as less intuitive compared to the blind user.

The test results suggest that several areas of audio-based gameplay may require particular attention of game designers. These include effective and accurate error messaging built into the game's sound design, precise timings and durations of key sound effects, and clear narrative and spatial distinction between different characters' voices and actions. While the overall soundscape and audio quality were well-received, additional sound cues could be implemented to signal errors, transitions between different states of the game, and the positions of characters. Character identities should be clearly distinguishable, and actions performed by non-player-controlled roles should be explicitly signaled, especially during non-gameplay sequences.

Interactions involving both the mouse and the keyboard were equally well received by the blind participant, although it was acknowledged that a keyboard-only input method should be an option for blind players who don't usually use a computer mouse.

Conclusions and Possible Next Steps

Research on accessibility in digital games for BLV users remains crucial, as this group is still frequently overlooked in the design process despite the growing adoption of inclusive and universal design principles. As a result, BLV players are often excluded from fully participating in digital entertainment, even though many express a strong interest in gaming. Their choices remain significantly limited due to insufficient accessibility and a lack of consideration of their needs in mainstream game development. Although BLV players have access to some games designed specifically for them, the subpar quality of many of these designs often leads to frustration and abandonment of the medium.

The findings highlight that the market for accessible games is still relatively underdeveloped. At the same time, they indicate a strong potential for improvement through more consistent application of accessibility standards, such as WCAG principles, and through active inclusion of BLV users in the design process. Game developers can take inspiration from successful community-driven projects aimed at and created by BLV gamers, incorporating more of their solutions into standard accessibility features. Despite many existing audio games being viewed as overly simplistic, they exhibit potential as a game medium that can be enjoyed equally by sighted and BLV players.

Future work will focus on further usability testing of the current game prototype, building on the preliminary evaluation conducted with three participants, in order to validate and expand the initial findings. In parallel, the development of the game will continue, including extending gameplay content and refining interaction mechanics based on user feedback. Particular emphasis will be placed on iterative design supported by continuous involvement of BLV users and designers, ensuring that accessibility remains an integral part of the development process.

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ICT to Support Inclusive Education – Universal Learning Design (ULD)

AI-Driven Cognitive Accessibility for People with Non-Visible Disabilities in Higher Education: A Conceptual Framework for Inclusive Digital Systems

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Abstract

Students with non-visible disabilities and neurodivergent profiles are increasingly present in higher education, but they often face difficulties when using complex digital learning and administrative systems. Current accessibility approaches mainly focus on sensory and physical impairments, offering limited support for cognitive accessibility. This paper proposes a conceptual framework that treats cognitive accessibility as a system-level property, enabled by AI-driven adaptation. Using higher education as an example, the framework shows how artificial intelligence can adjust interaction complexity, predictability, and user control in real time, without requiring users to disclose a disability. The framework is structured around four interconnected pillars: cognitive accessibility, AI-driven adaptive behavior, user control and transparency, and institutional inclusion. Overall, the paper introduces a human-centered approach to using AI for improving cognitive accessibility in higher education systems.

Introduction

Digital systems have become central to participation in higher education, shaping teaching, learning, assessment, and student support services. While these systems provide flexibility and scalability, they often impose substantial cognitive demands on users [1, 2].

For students with non-visible disabilities and neurodivergent profiles, such demands can result in cognitive overload, anxiety, and disengagement, even when systems are technically accessible. These barriers are typically associated with dense information structures, fragmented workflows, unpredictable interaction patterns, and high executive-function requirements rather than with perceptual access limitations. Consequently, compliance with established accessibility guidelines does not necessarily translate into inclusive participation in digital higher education environments [3-5]. Cognitive and neurodivergent conditions encompass a wide range of profiles, including ADHD, dyslexia, and autism, each associated with distinct interaction challenges and support needs.

Artificial intelligence has been widely adopted in educational technologies to support personalization and efficiency. Intelligent tutoring systems, recommender systems, and learning analytics platforms demonstrate the potential of AI to tailor content and interaction [5]. However, accessibility is often treated as a secondary concern, and AI is commonly deployed as an auxiliary tool rather than as a core mechanism governing system behavior. Moreover, many accessibility-oriented AI solutions focus on specific impairments, limiting their scalability and institutional integration [6, 7].

This paper proposes that digital systems should support cognitive accessibility as a core feature through AI-driven adaptation during user interaction. Instead of focusing on specific applications or technical development processes, it introduces a conceptual framework showing how AI-enabled systems can dynamically adjust to diverse cognitive needs in higher education. Using a human-centered design perspective, the framework emphasizes adaptable, inclusive system behavior that can also be applied to other domains beyond education.

Background and Related Work

Digital accessibility research has traditionally focused on ensuring access for users with sensory and physical impairments [2]. As a result, accessibility standards and guidelines have significantly improved interface-level access, particularly for users with visual or auditory disabilities. The literature indicates that research on AI-driven digital accessibility continues to prioritize sensory impairments, while cognitive and learning disabilities remain comparatively underrepresented. A systematic review highlights this imbalance and underscores the need for greater attention to cognitive accessibility within AI-enabled digital systems [8].

Cognitive accessibility addresses how users process information, regulate attention, and manage tasks within digital environments, emphasizing predictability, information structure, and executive functioning [3]. Cognitive accessibility has long been recognized as a critical dimension of digital accessibility; however, empirical research and concrete design guidance remain comparatively limited when contrasted with work addressing sensory and physical impairments [10]. Recent studies further confirm that, despite increased awareness, cognitive accessibility remains insufficiently operationalized in digital system design, with fragmented guidance and limited adoption in practice [11,12].

In educational contexts, cognitive accessibility is often discussed in relation to inclusive pedagogy and universal design for learning. While these approaches promote flexibility in content presentation and assessment, they rely primarily on static design principles and manual accommodations. Research on accessibility in higher education further indicates that such practices are frequently implemented in an ad hoc and reactive manner, rather than being embedded systematically within digital learning environments [1]. A recent systematic review of educational settings further confirms that cognitive accessibility is most often addressed through pedagogical adaptations rather than being embedded within the behavior of digital learning systems themselves [13]. Guidance from the W3C Cognitive and Learning Disabilities Accessibility Task Force further highlights that barriers for learners with cognitive and learning disabilities often arise from interaction complexity, language, and contextual demands, which are only partially addressed by existing educational and accessibility frameworks [5].

Recent advances in artificial intelligence have increased interest in adaptive and personalized digital systems in education and assistive technology. In educational contexts, AI studies highlight how such systems can personalize learning experiences, while assistive technology research explores AI-based tools that support people with disabilities. Human-centered AI research emphasizes that when systems adapt automatically, users should understand what is happening, trust the system's behavior, and be able to control or override it if needed [9]. For example, if a system simplifies the interface after detecting user difficulty, it should clearly indicate why this change occurred and allow the user to return to the original layout. This is especially important in situations where automated system behavior may affect user autonomy and trust. Related work in human–AI interaction also shows that explainability, user control, and clear interaction design are essential for adaptive systems that users can understand, trust, and use effectively [14]. In addition, previous studies on assistive technology have shown that participatory and user-centered design can improve accessibility systems, especially when they are designed to support not only sensory impairments but also cognitive, interactional, and usability needs [15].

Building on these findings, extended usability evaluation, training-oriented interaction design, and systematic user requirements elicitation are essential for the acceptance, effective use, and long-term adoption of assistive digital systems, beyond interface-level accessibility alone [15,16]. However, adaptive systems that lack transparency may increase cognitive effort and reduce user autonomy, especially for people with non-visible disabilities [17]. In addition, accessibility is often treated as a secondary concern in AI system design rather than as a core system requirement [6]. As a result, research on AI fairness shows that AI systems often fail to address the needs of people with disabilities, leading to exclusionary or unequal outcomes when accessibility is not integrated from the outset [7]. These

findings highlight that fairness for people with disabilities requires accessibility to be embedded throughout the AI development lifecycle rather than added later as a post hoc adaptation.

Beyond established accessibility standards, recent guidance from the World Wide Web Consortium (W3C) emphasizes that traditional guideline-based approaches only partially address the needs of people with cognitive and learning disabilities. W3C cognitive accessibility documentation highlights that many barriers arise from design, structure, language, and interaction complexity, rather than from sensory or physical access alone. As noted by the Cognitive and Learning Disabilities Accessibility Task Force, compliance with the Web Content Accessibility Guidelines (WCAG) does not necessarily ensure usability or independent access for users with cognitive and learning disabilities. Instead, additional objectives and design patterns are needed to address challenges related to attention, memory, executive functioning, and predictability. Although this guidance is not required for WCAG conformance, it has been shown to significantly improve accessibility and usability for people with cognitive and learning disabilities [3]. These considerations reinforce the need for accessibility approaches that go beyond compliance-based models and treat cognitive accessibility as a flexible, inclusive, and system-level concern [3,5]. In many cases, cognitive accessibility challenges arise from interaction design and task structure rather than from interface-level barriers alone [5]. Complementary work in human-centered design further highlights the importance of considering diverse values and user capabilities in complex digital systems, while recent studies on adaptive learning systems show that managing cognitive load during interaction supports more effective use in such environments [18,19]. Despite growing interest in inclusive AI, there is still a lack of system-level conceptual frameworks that explicitly connect AI-driven adaptive behavior with cognitive accessibility in higher education. This gap motivates the framework proposed in this paper.

Cognitive Accessibility as a System Requirement

Building on this perspective, cognitive accessibility refers to the extent to which digital systems align with users' cognitive processes, including attention regulation, information processing, memory, and executive functioning. Unlike traditional accessibility approaches that focus primarily on perceptual barriers, cognitive accessibility emphasizes how interaction complexity, predictability, and information organization shape users' ability to engage effectively with digital systems.

In higher education, digital systems require sustained engagement, coordination of multiple tasks, and interaction with complex information structures. These demands highlight the limitations of guideline-based and accommodation-driven approaches, which provide limited support for adapting dynamically to users' cognitive needs [3,5,13]. This paper conceptualizes cognitive accessibility as a system requirement rather than as an interface feature or individualized accommodation. From this perspective, accessibility emerges through the behavior of digital environments, including how information is structured, how interactions are paced, and how users are supported in managing tasks over time. Artificial intelligence enables this shift by allowing systems to adapt dynamically during active user interaction based on observed interaction patterns.

Conceptual Framework for AI-Driven Cognitive Accessibility

The proposed framework identifies the key interacting system properties that coexist in higher education digital systems during active user interaction. Within this framework, AI-driven adaptive behavior serves as the central mechanism for enabling cognitive accessibility. The framework adopts a design-oriented and human-centered perspective [9,18] and is structured around four interrelated pillars that continuously interact as users engage with the system.

These pillars function together to shape adaptive system behavior. The first pillar, cognitive accessibility, defines the desired system outcome. It emphasizes reducing unnecessary cognitive load, enhancing predictability, and supporting executive functioning through structured interaction and information

presentation. The second pillar, AI-driven adaptive system behavior, conceptualizes artificial intelligence as a dynamic control layer governing system adaptation during user interaction. AI mechanisms monitor interaction patterns and adjust system responses accordingly [9,14]. AI-driven adaptation can be operationalized through continuous analysis of interaction signals such as navigation patterns, response latency, and task completion behavior. Based on these signals, the system dynamically regulates interaction complexity, information density, and workflow structure. For example, the system may simplify navigation paths, provide step-by-step guidance, or reduce concurrent information presentation when cognitive overload is detected. Adaptation focuses on regulating interaction complexity and pacing rather than categorizing users according to predefined profiles or diagnostic labels.

The third pillar addresses user control, transparency, and self-advocacy. Users should be able to understand why adaptations occur, modify system responses, and override automated decisions when necessary [14]. Self-advocacy is reframed as a supported interaction capability rather than an individual responsibility, enabling inclusive participation without requiring formal disclosure of disability status. Trust is a critical factor in AI-driven adaptive systems. Users need to understand when and why adaptations occur in order to maintain confidence in the system [9,14]. Transparent feedback, predictable system behavior, and the ability to override automated adaptations are essential to ensure that adaptive support enhances rather than reduces user autonomy.

The fourth pillar, institutional inclusion, situates cognitive accessibility within the broader organizational context of higher education. Institutional support structures, such as accessibility units and governance mechanisms, are essential for ensuring accountability, scalability, and ethical deployment.

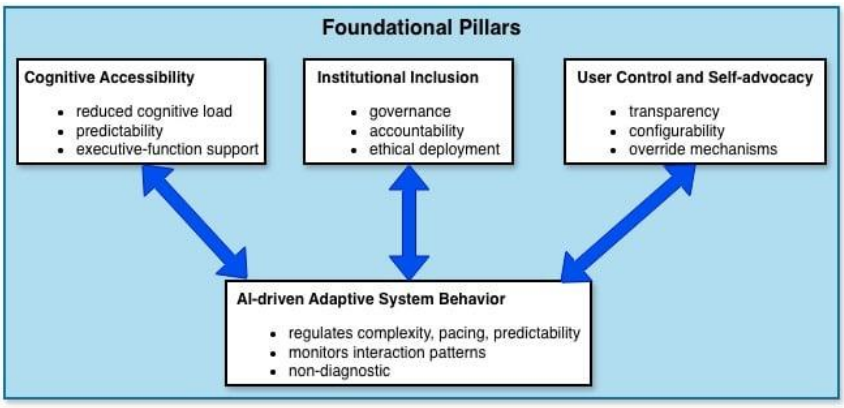


Figure 1: System-level conceptual framework for AI-driven cognitive accessibility in higher education, illustrating the relationship between cognitive accessibility, AI-driven adaptive system behavior, user control and self-advocacy, and institutional inclusion.

Implications and Preliminary Considerations

The proposed framework encourages higher education institutions to move beyond compliance-based accessibility and adopt more adaptive and inclusive digital systems. As a conceptual framework, it has not yet been empirically validated. However, it can support future evaluation through system-level analysis, synthetic interaction modeling, and expert-based methods. These approaches make it possible to assess interaction complexity, predictability, and user control without requiring the immediate involvement of vulnerable populations. For example, during course registration, an adaptive system could detect prolonged interaction or repeated navigation errors and respond by simplifying the interface, highlighting relevant options, or guiding the user step by step.

While the framework focuses on higher education, it is flexible and can also be applied to other domains. Similar cognitive demands also exist in other complex digital environments, suggesting broader use of the framework.

Conclusions and Possible Next Steps

Addressing the needs of individuals with cognitive and intellectual disabilities requires rethinking how accessibility is conceptualized and embedded within digital systems. This paper argues that cognitive accessibility should be treated as a system-level requirement, supported through AI-driven adaptive behavior rather than relying solely on static guidelines or post hoc accommodations. The proposed framework contributes a human-centered conceptual model for integrating cognitive accessibility into higher education digital environments through four interrelated pillars: cognitive accessibility, AI-driven adaptive system behavior, user control and transparency, and institutional inclusion. By positioning accessibility as an emergent system property enabled through adaptive AI behavior, the framework offers a human-centered and institutionally grounded perspective on inclusive digital systems. Recent studies further emphasize that accessibility must be embedded systematically into design processes rather than treated as an afterthought [20]. Related studies on assistive technology acceptance further show that long-term adoption is also shaped by perceived effort, usability expectations, and trust in adaptive technologies [21]. As a conceptual model, the framework has not yet undergone empirical validation. Future work will focus on prototype development and empirical evaluation with neurodivergent students and domain experts, while also exploring the role of emerging AI paradigms in supporting cognitive accessibility across domains.

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Blind and Visually Impaired Students in Computer Science: Institutional Conditions and Paths Towards Proactive University Support in Austria, Ireland and Slovenia

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Abstract

Blind and visually impaired students are massively underrepresented in computer science degree programmes in Austria, Ireland and Slovenia, with enrolment rates often at zero or at least minimal. The paper is based on the comprehensive institutional report of the EU-funded Access2CS project (Access2CS, 2026). It presents the results of desk research, qualitative interviews and a systematic literature review, summarises the main obstacles and proposes evidence-based, action-oriented recommendations for universities. The aim is to facilitate a shift from reactive, case-by-case adjustments to proactive, subject-specific inclusion.

Introduction

The Access2CS project addresses the underrepresentation of blind and visually impaired students in computer science degree programmes. This discipline is particularly challenging due to its high visual component. Although international and national legal requirements, such as the UN Convention on the Rights of Persons with Disabilities (2006), set clear standards for accessibility, the desk research data indicate minimal or no enrolment of blind and visually impaired students at the universities analysed. This paper focuses on the findings from the three methodological pillars – desk research, interviews and a literature review – and derives concrete recommendations from them, aimed at bringing about a sustainable transformation of institutional structures. The analysis is based on a triangulation of various data sources to establish a valid and practice-relevant foundation for the recommendations.

Methodology

The empirical basis of this paper is based on three complementary methodological approaches. Firstly, the desk research comprises an analysis of national legislation, internal university guidelines, services provided by support centres, and other publicly accessible data sources such as university websites. Secondly, nine semi-structured qualitative interviews were conducted with staff from disability services at universities in Austria (five interviews), Ireland (three interviews) and Slovenia (one interview). These took place in 2025 online via Zoom, Microsoft Teams or in person, lasted between 30 and 60 minutes, were recorded, transcribed and analysed using thematic coding. Thirdly, the systematic literature review, conducted in accordance with the guidelines of Kitchenham and Charters (2007), forms the scientific basis; 1,694 articles were identified in the Scopus, ACM, Web of Science and ERIC databases, and following screening with Rayyan, 48 relevant articles were included.

The interviews were based on standardised guiding questions that focused on services offered, organisational responsibilities, training opportunities, specific challenges in computer science education, and feedback mechanisms. The overall analysis placed particular emphasis on context-specific barriers and support structures in the field of computer science.

Desk research findings: Legal framework

All three countries examined have ratified the UN Convention on the Rights of Persons with Disabilities (2006), which mandates accessibility and reasonable accommodation for students with disabilities. In Austria, the Federal Act on the Equality of Persons with Disabilities (BGStG, 2005; RIS, 2023) and the Universities Act (UG, 2002; RIS, 2023) form the legal basis. These laws oblige universities to provide accessible facilities as well as individual adjustments such as extended examination times or alternative assessment formats. This is supplemented by the Disability Employment Act (BEinstG, 2023), which specifically addresses labour market-related aspects for graduates of computer science programmes. Nevertheless, the analyses show that subject-specific responsibilities for computer science programmes are fragmented at faculty level, with no central coordination body.

Ireland relies on a comprehensive legal framework that includes the Disability Act (2005), which mandates needs assessments and access to services. The ALTITUDE Charter for Universal Design for Learning (Atlantic Technological University, 2024) and EU regulations on the accessibility of websites and mobile applications (2016) and products and services (2019/2023) promote systemic approaches to inclusion. The Irish Human Rights and Equality Commission monitors implementation, but practical experience with blind and visually impaired students in computer science programmes remains limited.

Slovenia offers a particularly coherent framework through the Equal Opportunities Act for Persons with Disabilities (ZIMI, 2010), the Anti-Discrimination Act (ZVarD, 2016), the Higher Education Act (ZViS, 2021) and the NAKVIS Accessibility Guidelines (2022). These laws and guidelines define physical, informational and communicative accessibility and enable annual reviews of individual adjustments. Nevertheless, computer science-specific measures have not yet been sufficiently developed.

In summary, all states have a clear legal obligation to provide for students with disabilities. However, these general legal requirements rarely translate into specific, subject-related regulations for teaching computer science.

Desk Research Findings: Support Services and Structures

Service centres for students with disabilities exist in all three countries; however, these primarily serve various disability groups and only partially meet the specific requirements of computer science teaching. Austrian service centres offer advice, technical aids such as screen readers and Braille displays, as well as exam accommodations. However, specially equipped workstations for computer science teaching are rare, and the adaptation of visual learning materials such as diagrams or graphics – for example, through tactile models – is inconsistent.

Ireland has national organisations such as the National Disability Authority (2026) and the Centre for Excellence in Universal Design (2026), as well as university Disability Support Services, supplemented by networks such as AHEAD and DAWN. General support services such as writing centres or financial support through SUSI exist, but there is a lack of standardised processes for blind and visually impaired students in computer science education.

Slovenia combines university support services such as the 'Mobile Support' team, buddy schemes and the Association of Students with Disabilities (DIS, 2026) with a special status for individual adjustments.

In all countries, feedback on the needs of blind and visually impaired students in computer science courses remains informal and lacks systematic monitoring.

Interview Findings

The nine interviews conducted – five in Austria, three in Ireland and one in Slovenia – highlight the existing gaps in practice. Of the universities interviewed in Austria, only one has enrolled a blind or visually impaired student on a computer science programme. The support offered is predominantly

reactive. Particularly serious is the lack of specialised software solutions and corresponding training for teaching staff.

Irish interviewees highlight the strengths of the Disability Support Services, which provide screen readers such as NVDA and magnifying software. Nevertheless, there is a lack of awareness among staff.

In Slovenia, buddy schemes, faculty contact persons and annual reviews of accommodation measures support the five blind and visually impaired computer science students currently enrolled. However, training opportunities for teaching staff remain voluntary, and subject-specific programmes are lacking.

Common themes emerging from all interviews include the low visibility of blind and visually impaired students in computer science classes, fragmented responsibilities across different services, and an urgent need for proactive measures and targeted training.

Results of the Systematic Literature Review

The systematic literature review comprises 48 articles which confirm that institutional barriers are the central problem for blind and visually impaired students in computer science courses (Butler et al., 2017). Universities often struggle to provide accessible teaching materials in time, to allocate adequate staff resources, and to ensure effective coordination between disability services, academic departments and IT departments (McCall, 2019). Widely used teaching materials in computer science education are largely incompatible with screen readers, meaning that blind and visually impaired students have to make a disproportionately high additional effort (Bonfim et al., 2021). Although Universal Design for Learning is promoted as a solution, it is rarely applied in computer science teaching and requires structured training for teaching staff (Banks et al., 2024). Assistive technologies and peer mentoring programmes have proven effective, but require firm institutional embedding.

The perspectives of the students themselves highlight the disproportionate burden placed on their basic participation in lessons, as well as increased risks of dropping out due to systemic gaps that remain unaddressed.

Key Barriers

Analysis of the three data sources reveals four key types of barrier: Technical barriers include inaccessible teaching materials and software that are not compatible with screen readers, as well as procurement processes that ignore the needs of blind and visually impaired students. Institutional barriers are evident in the prevalence of reactive adjustments, the lack of specific coordinators for computer science teaching, and poor coordination between services, faculties and IT departments. Staffing capacity gaps result from insufficient training on subject-specific accessibility. Finally, monitoring is limited to informal feedback, with no systematic metrics on blind and visually impaired students in computer science education.

Recommendations for Further Development

The following five priority areas are based on the empirical findings and offer concrete, actionable pathways for the sustainable transformation of institutional structures. Each recommendation integrates evidence from desk research, interviews and a literature review, as well as detailed implementation steps including responsibilities, timelines and evaluation criteria.

Recommendation 1: Appointment of Designated Coordinators for Blind and Visually Impaired Students in Computer Science Degree Programmes

Universities require clear accountability structures with permanently appointed coordinators who coordinate the various services – namely disability services, computer science faculties and IT

departments. These individuals ensure that teaching materials are made accessible, ensure that suitable technical aids are procured, and foster effective collaboration between departments.

Recommendation 2: Systematic Quality Assurance and Monitoring

The current informal feedback system must be replaced by fixed measurement tools specifically targeting the experiences of blind and visually impaired students in computer science classes. Regular surveys, structured feedback on courses and open enrolment data provide the missing overview that desk research and interviews unanimously call for.

Recommendation 3: Targeted Training for Teaching Staff

Targeted training for lecturers and tutors is essential to ensure they know how to adapt teaching materials for visually impaired students – for example, through alternative descriptions of images or different assessment methods. The interviews clearly show that this is where the greatest knowledge gaps lie.

Recommendation 4: Establish Structured Peer Mentoring Programmes

A network connecting blind and visually impaired students with more experienced fellow students or graduates helps combat loneliness and insecurity. Slovenia's buddy systems already demonstrate how well this works.

Recommendation 5: Proactive Curriculum Design with Universal Design for Learning

Accessibility must be a priority right from the planning stage of new courses – for example, through clear descriptions of images, diverse assessment methods and appropriate teaching materials. Guidelines such as ALTITUDE (2024) or NAKVIS (2022) provide a roadmap for this.

Conclusions

The analysis of desk research, qualitative interviews and a systematic literature review shows weaknesses within the higher education systems in Austria, Ireland and Slovenia. Despite legal frameworks and existing support structures such as Disability Support Services and Mobile Support, institutional barriers remain evident. Technical incompatibilities in teaching materials, staff shortages and coordination deficits between services prevent effective inclusion. The extremely low enrolment rates in computer science programmes do not indicate a lack of motivation or aptitude on the part of the students, but rather inaccessible learning environments.

The recommendations developed show a path from reactive to proactive inclusion

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Peer Counselling to Support Blind and Visually Impaired Pupils in Their Transition to Higher Education

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Abstract

Blind and visually impaired pupils face substantial barriers when considering and entering higher education, including inaccessible information on study options, uncertainty about available support, and limited contact with visually impaired students who have university experience. This paper presents a structured peer counselling model in which blind and visually impaired university students support school pupils in their school-to-university transition. The initiative combines a needs and barriers analysis, the design of an accessible training programme for student peer counsellors, and implementation of a first pilot cycle. The pilot includes individual and group sessions, topic-focused workshops, and university visits, accompanied by regular supervision. A mixed-methods evaluation examines feasibility, perceived usefulness, and changes in pupils' confidence, study orientation, and awareness of support structures. The results provide an evidence-based peer counselling approach with transferable guidance materials and recommendations for embedding user-driven peer support into school and university structures.

Introduction

Blind and visually impaired pupils remain significantly underrepresented in higher education, even where institutional disability support services exist. The transition from school to university constitutes a particularly critical phase during which many potentially qualified pupils abandon their higher education aspirations. This vulnerability arises from three primary barriers: inaccessible study programme information, uncertainty regarding available support structures and reasonable accommodations, and limited opportunities to connect with visually impaired students who can provide authentic insights into university life.

The Bridge2Uni project responds to these challenges through a structured peer counselling model that connects visually impaired university students with school pupils preparing for higher education. By training university students as peer counsellors, the approach creates a sustainable system of experience-based support that complements rather than replaces existing institutional services. This user-driven methodology leverages the unique experiential knowledge possessed by peers who have successfully navigated the same transition, offering practical guidance and emotional support of a kind that formal support structures often cannot provide.

The Need for Transition Support

Despite decades of inclusion policies and legal frameworks promoting accessibility, visually impaired students continue to face disproportionate barriers when entering higher education. The transition from school to university is a particularly sensitive stage, where the risk of dropping out is highest and important decisions about study programmes and career paths are made. Even in countries with established disability services, pupils frequently encounter inaccessible admissions information, lack of clarity about accommodation procedures, and experience social isolation due to the absence of relatable role models.

Existing support mechanisms, while valuable, often fail to address the specific psycho-social dimensions of this transition. Professional counsellors and disability advisors can provide procedural guidance and

legal information, but they cannot replicate the authentic insights that come from peers who have personally navigated academic demands, social integration challenges, and self-advocacy strategies within the higher education environment. The absence of such peer-to-peer exchange leaves many visually impaired pupils uncertain about their ability to succeed at university, contributing to unnecessarily low enrolment rates.

Peer support approaches in inclusive education consistently demonstrate enhanced participation, self-confidence, and sense of belonging among learners with disabilities. Structured mutual support among individuals sharing similar experiences addresses both practical navigation challenges and the psychosocial dimensions of inclusion that formal services frequently overlook. When delivered through trained peer counsellors, this support carries credibility and resonance, as recipients recognise that counsellors truly understand both the challenges and the solutions.

Theoretical Foundation and Supporting Evidence

The Bridge2Uni model builds on a foundation of peer support research showing clear benefits for disabled students entering higher education. Costa et al. (2024) found that peer mentoring circles improved self-advocacy skills, institutional navigation abilities, and motivation to pursue higher education among students both with and without disabilities. Their research highlighted the particular value of regular facilitated peer interaction for both academic adjustment and social integration during the critical first university year.

There is more proof that peer relationships can help people with visual impairments. Heppe et al. (2015) conducted a trial demonstrating that mentoring interventions substantially enhanced social participation among adolescents with visual impairments. Their findings highlight the efficacy of structured peer relationships in addressing the unique social and practical challenges faced by this population during key life transitions.

Structured training emerges as important for mentoring success. Lunsford et al. (2023) showed that online mentor training programmes for supporters of youth with visual impairments improved mentor confidence, role clarity, and ability to provide appropriate guidance. This preparation proved essential for ensuring mentoring relationships remained effective and sustainable over time.

The current literature on transition support focuses on collaboration between schools, families and universities. This collaboration is important for helping students find their way around, making materials accessible to all and using technology to support them. However, Travers and Irland (2024) note a persistent gap: the absence of formalised roles for visually impaired university students themselves, despite these individuals possessing precisely the experiential knowledge needed to guide younger peers through higher education navigation. In a broader perspective on disability inclusion in higher education, Glava and Ki-Glava (2023) argue that peer support can strengthen participation, belonging, and mutual learning, particularly when it is embedded structurally rather than offered as an isolated activity. This shows the relevance of peer-based approaches for students with disabilities and helps situate the Bridge2Uni model within current debates on inclusive higher education.

The Bridge2Uni Peer Counselling Model

The Bridge2Uni model integrates several phases that together create a comprehensive, evidence-based approach to transition support. Initial needs analysis combines literature review with qualitative data collection through semi-structured interviews and focus groups involving pupils, university students, teachers, and parents. This empirical foundation identifies specific barriers and expectations, ensuring subsequent interventions respond directly to identified needs rather than assumptions.

Building on these insights, the model centres on a comprehensive training programme for visually impaired university students. The curriculum systematically addresses study programme orientation and

admissions procedures, accessibility standards and reasonable accommodation processes, assistive technologies and digital tools, self-advocacy rights and responsibilities, and reflective practice with clear role boundaries. All training materials are developed in screen-reader-compatible formats and piloted with visually impaired students to ensure practical usability and accessibility.

Counselling offers individual one-to-one sessions, small group meetings, and themed workshops addressing application procedures, study organisation techniques, and assistive technology applications. Where feasible, university campus visits provide concrete exposure to higher education environments and allow pupils to move beyond abstract expectations. Regular meetings help the peer counsellors deal with any problems they might have, talk about what they have been doing, and make sure the quality of their counselling stays high while looking after their own wellbeing.

A strength of the model lies in its understanding of peer counselling as an additional layer of support rather than a substitute for professional services. It does not attempt to replace disability support offices, teachers, family guidance, or formal counselling. Instead, it adds a form of support rooted in lived experience. This distinction is important because transition to higher education is not only an administrative process but also an emotional and identity-related one. Pupils do not only need information about application deadlines, study formats, and accommodation procedures; they also need reassurance that university is a realistic and attainable option for them. Hearing from peers who have already negotiated inaccessible systems, built social networks, and developed effective coping strategies can make higher education appear more imaginable and more achievable.

Training Curriculum: From Knowledge to Practice

The training curriculum uses several connected modules to turn theoretical knowledge into practical counselling skills. Participants first learn about the university landscape, including how to choose study programmes, how the faculties are organised, what is expected of students, and how the support services are set up. This foundation helps counsellors to discuss higher education in realistic and different ways, instead of using general terms.

Accessibility training addresses procedural and practical knowledge essential for university success. Counsellors engage with reasonable accommodation processes, accessible materials, alternative assessment formats, and the role of assistive technology in academic life. This content is particularly important because many school pupils are unfamiliar with the formal mechanisms that structure inclusion in higher education. The counselling relationship therefore has the potential not only to reduce uncertainty but also to increase autonomy.

Practical navigation is just as important. The course includes discussion of things like how to find your way around campus, how to organise your studies, time management, how to talk to your teachers, and how to get involved in society. These areas are often based on personal knowledge and strategies, so they are especially good for learning with other people. Counsellors are not just expected to pass on general information. They are also encouraged to think carefully about their own experiences and use this to help others.

Another important part of the training concerns self-advocacy. Higher education often requires students to explain their needs, request adjustments, and negotiate accessibility barriers in interactions with academic staff and administration. Preparing peer counsellors to discuss these processes is therefore important. At the same time, the curriculum addresses role boundaries, active listening, empathy, and self-care. Peer counsellors are not expected to become therapists or professional social workers. Rather, they are prepared for a clearly defined supportive role that is reflective, bounded, and embedded in supervision.

Pilot Implementation: From Concept to Practice

The pilot phase translates the conceptual model into a structured counselling process. Trained peer counsellors are matched with blind and visually impaired pupils who are considering higher education or who are in the final years of secondary schooling. The counselling process is designed to unfold over time, allowing relationships of trust to emerge and enabling counselling topics to develop gradually in response to pupils' needs, interests, and decisions.

At the beginning of the pilot, attention is given to getting to know each other, clarifying expectations, and opening up discussion about possible educational futures. For many pupils, this stage is likely to be the first time they can speak in depth with a visually impaired university student about what studying actually involves. As the process continues, more specific topics such as degree programme selection, admission procedures, preparation for university life, accommodation requests, and assistive technologies are addressed.

Where possible, the pilot includes visits to higher education environments. Such experiences are important because they allow pupils to experience the material and social reality of university spaces. Visiting lecture halls, libraries, support offices, and campus environments can reduce anxiety and support more concrete decision-making. These experiences are particularly valuable when combined with peer explanation and reflection, because they connect institutional structures with lived experience.

Why the Project Matters

The importance of Bridge2Uni lies in the fact that it addresses a problem that is practical, structural, and symbolic. On a practical level, the project responds to concrete informational and procedural barriers faced by blind and visually impaired pupils. On a structural level, it develops an organised model that can be embedded in existing educational support systems. On a symbolic level, it challenges persistent assumptions that higher education is only conditionally accessible for students with visual impairments.

By focusing on peer counsellors as knowledgeable actors, the project also redistributes expertise. Expertise is not located only in professionals, institutions, or formal guidance documents, but also in the lived experiences of visually impaired students themselves. This recognition is important for inclusive education because it values students with impairments not only as recipients of support but as contributors, advisors, and co-creators of more inclusive pathways.

The project is also important because of its dual impact. It supports pupils in developing confidence, orientation, and awareness of possibilities, while simultaneously creating developmental opportunities for peer counsellors. Through training and counselling practice, counsellors can strengthen communication skills, reflective ability, leadership, and advocacy competence. In this way, the model produces benefits that extend beyond the immediate counselling encounter.

More broadly, Bridge2Uni contributes to ongoing discussions about participation in higher education. If blind and visually impaired students remain underrepresented, this cannot be understood simply as a matter of individual choice. It reflects institutional, informational, and social barriers that shape educational pathways. A peer counselling model cannot remove all structural inequalities, but it can intervene meaningfully at a decisive transition point. It can make access to higher education more imaginable, more navigable, and more socially supported.

Discussion

The Bridge2Uni model suggests that peer counselling has potential when it is conceptualised not as an informal add-on but as a structured and supported educational intervention. Peer support can foster participation and belonging, mentoring can strengthen social participation among visually impaired

young people, and mentor training improves the quality and clarity of support relationships. Taken together, these insights indicate that the success of peer counselling depends not simply on matching people with similar experiences, but on creating an organised framework in which these experiences can become pedagogically meaningful.

At the same time, the project also points to challenges. Recruitment may be difficult in contexts where the number of visually impaired students is small. Accessibility must be ensured consistently across all communication, materials, and digital environments. Counsellors need support so that the role remains manageable and does not become emotionally overburdening. Furthermore, institutions need to recognise peer counselling as a part of transition support rather than as a voluntary supplement with unclear status.

The project is therefore best understood as both a practical intervention and a conceptual contribution. It demonstrates how lived experience can be mobilised in structured ways to support educational transitions, and it offers a model that can inform future work in inclusive higher education, disability support, and peer-based learning.

Conclusion

Bridge2Uni presents a compelling model for supporting blind and visually impaired pupils in the transition to higher education through structured peer counselling. By combining a needs-based design, accessible training, supervised implementation, and mixed-methods evaluation, the project responds directly to a gap in existing transition support. It recognises that successful access to higher education depends not only on formal accommodations and institutional procedures but also on confidence, belonging, realistic expectations, and the presence of relatable role models.

The project matters because it positions visually impaired university students as holders of valuable experiential knowledge and as active contributors to inclusive education. In doing so, it expands understandings of support, participation, and expertise within the transition process. If the pilot confirms the anticipated benefits, the resulting model, training resources, and recommendations may offer a transferable framework for institutions seeking to improve educational pathways for blind and visually impaired learners.

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New Methods for Creating Accessible Material in Higher Education

Tactile IPA Chart with Audio Feedback for Visually Impaired Students

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Abstract

Learning English pronunciation is particularly challenging for Japanese students with visual impairments who often lack access to formal phonetic instruction. This paper proposes a low-cost, intuitive learning system that utilizes a standard laptop, a webcam, and swell-paper tactile sheets to teach the phonetic symbols of English using the International Phonetic Alphabet (IPA) vowel chart. By employing augmented reality (AR) markers and the Google MediaPipe library, the system tracks finger positions to provide immediate audio feedback when tactile IPA symbols are touched. Three specialized tactile sheets were developed to help learners associate symbol shapes with articulatory features and tongue positions. A preliminary evaluation with visually impaired university students showed high levels of engagement and positive feedback regarding the system's attractiveness and interactivity. Participants commented that predicting how to pronunce symbols with the IPA chart and listening to the audio afterward was a "game-like" experience.

Introduction

Learning English pronunciation is widely recognized as one of the most challenging aspects of English language acquisition for Japanese learners. While listening to spoken English audio files and imitating them is generally considered an effective learning method and talking with AI software is common and effective in these days, mastering phonetic symbols enables a more systematic approach to learning English pronunciation. However, it has been reported in domestic research [1] that most of Japanese students lack opportunities to acquire accurate knowledge of phonetic symbols in school even though phonetic symbols are printed in their English textbook. We can infer that students experience frustration when encountering phonetic symbols in the textbooks. Furthermore, the paper notes that even English-Japanese dictionaries published in Japan use different notations for some phonetic symbols. We believe this inconsistency causes confusion among students, leading them to continue learning English without understanding the system of phonetic symbols, even though they would have opportunities to read the symbols and pronounce them in the lecture of English in their class.

A similar situation might exist in special schools for the blind and visually impaired. Several severely visually impaired students in our university remarked they did not receive instruction on phonetic symbols, despite the fact that Braille codes for the phonetic alphabet have been developed [2] and are included in English textbooks used in their schools. One blind student reported that while he recognized the Braille patterns of the phonetic symbols, he could not understand them; consequently, he stated that he simply skipped over them whenever they appeared.

To address these issues and assist to learn phonetic symbols, several projects have explored in other countries. In these projects, tactile cards made from swell-paper are used to represent the shapes of the International Phonetic Alphabet (IPA) [3][4]. Swell-paper, which is coated with heat-reactive microcapsules, is widely used in the field of special education for the blind. While results indicate that tactile representations of phonetic symbols are readily understandable for blind students, accessing the associated audio information remains a multi-step process. Using these tactile cards, learners must identify URLs printed on the cards and then switch from tactile exploration to operating an external,

internet-connected device. Although tactile cards effectively help students memorize individual symbol shapes, they provide limited support for understanding the spatial organization and the positional relationships within the IPA chart. To overcome these limitations, this paper proposes an intuitive and practical system for teaching the IPA including its chart to students with severe visual impairments.

The primary research question of this project is to investigate which types of learning materials or educational systems effectively facilitate the acquisition of phonetic symbols for students with severe visual impairments. In developing the prototypes, we prioritized feasibility, aiming to create a system that is as cost-effective and accessible as possible.

Proposed System

As an initial step, we focused on a vowel chart of modern American English because vowel is fundamental knowledge for pronunciation, and we believe that the chart is useful for systematically learning the structure of English vowels. Although multiple vowel classification schemes exist, we adopted a fifteen-vowel classification to minimize complexity.

We first considered developing a tactile learning system in which audio feedback is generated directly from locations touched on a tactile IPA vowel chart. Such functionality can be achieved using commercially available products. For example, a tactile system with audio feedback can be created using the Tactonom Reader Flex [5] or the IVEO hands-on learning system [6]. However, these dedicated devices are costly and difficult for most of special schools for the blind to obtain. To promote wider adoption in special education settings, we designed the proposed system using low-cost and readily available components: a standard laptop computer and sheets of swell-paper, which are already commonly used in daily lectures in the school.



Figure 1: System overview. Left column instructs components of the system and right column explains how it works.

Figure 1 presents an overview of the system. Each tactile sheet includes four augmented reality (AR) markers printed in blue ink at the corners. Because swell-paper does not react to blue ink, the AR marker areas remain flat, while the tactile symbols printed in the central area are raised. A web camera mounted on the laptop captures images of the tactile sheet, including the AR markers and the user's hands. The system detects the positions of the user's finger joints using the Google MediaPipe library, the software then corrects perspective distortion by transforming the captured trapezoidal image into a rectangular coordinate space based on the detected AR marker positions. Figure 2 shows the image captured by the webcam (left) and the transformed image based on the four AR markers (right).

Detected positions of the user's finger are shown as color dots. Following this transformation, audio feedback corresponding to specific IPA symbols is generated when the detected finger positions remain within preset coordinates. In the current implementation, an audio file representing a vowel pronunciation is played when both index fingers simultaneously touch the same phonetic symbol. Audio playback stops when these index fingers move apart from each other. This interaction design allows learners to explore the chart tactually while receiving immediate auditory feedback without relying on external devices and additional operations.

In case the user moves the position of the tactile sheet, the conversion parameter from trapezoidal to rectangular images are changed automatically. This function does not work if the user covers AR Marker(s) with hands though, once he/she releases the hands on the sheet, it works immediately. To prevent the tactile sheet from moving, non-slip mat placed on the table is considered useful.

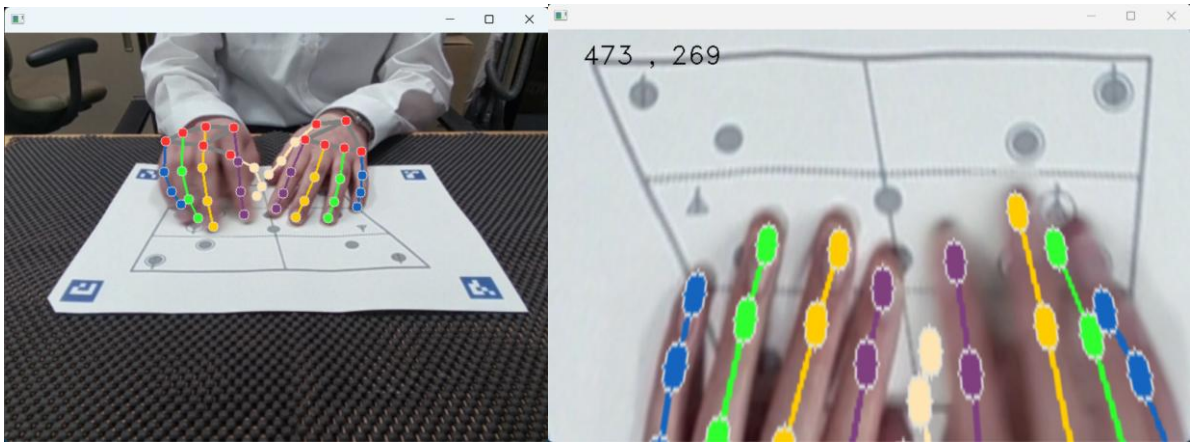


Figure 2. An image captured by the webcam on a laptop (left) and transformed image using Augmented Reality Markers

Evaluation of the System

We prepared three types of tactile sheets, as shown in Figure 3. The first sheet (a) coordinates with presents the fifteen vowel symbols arranged in a simple grid of five rows and three columns. This sheet is designed to support memorization of individual symbol shapes and their corresponding pronunciations. The second sheet (b) represents an IPA vowel chart using fifteen tactile icons positioned according to their articulatory locations within the chart. To facilitate tactile discrimination, the icons are designed with simple geometric features: circular shapes indicate monophthongs, while triangular shapes represent diphthongs. In addition, an outer circular line denotes rounded lip articulation, and a vertical line indicates tongue tension. Through this design, learners can acquire not only information about tongue position, but also articulatory features such as lip rounding and tongue tension by tactile exploration. The third sheet (c) presents the IPA vowel chart using the shapes of the phonetic symbols themselves. This sheet is intended to help learners associate each phonetic symbol with its corresponding tongue position within the IPA chart.

The user evaluation was conducted with approval from the university's ethics review committee. Two university students with visual impairments participated in the study: one male and one female, both in their early twenties and interested in learning English. The male participant was totally blind, whereas the female one had severe visual impairment. Both participants regularly use screen reader software and Braille. During the evaluation session, they tried to use the proposed system to study the shapes and pronunciations of fifteen American English vowel sounds. They explored three types of tactile sheets sequentially and spent approximately 30 minutes in total, with more than five minutes devoted to each sheet, while receiving audio feedback. Explanations of articulatory features - such as tongue position, lip rounding, and tongue tension - were provided by teaching staff during exploration of the IPA charts. Pronunciation audio for each vowel was presented through the laptop's built-in speakers at an appropriate volume.

After completing the learning session, participants were asked to complete the User Experience Questionnaire (UEQ) [7] via Microsoft Forms on their own smartphones. In addition, semi-structured interviews were conducted to collect qualitative feedback on usability and learning experience.

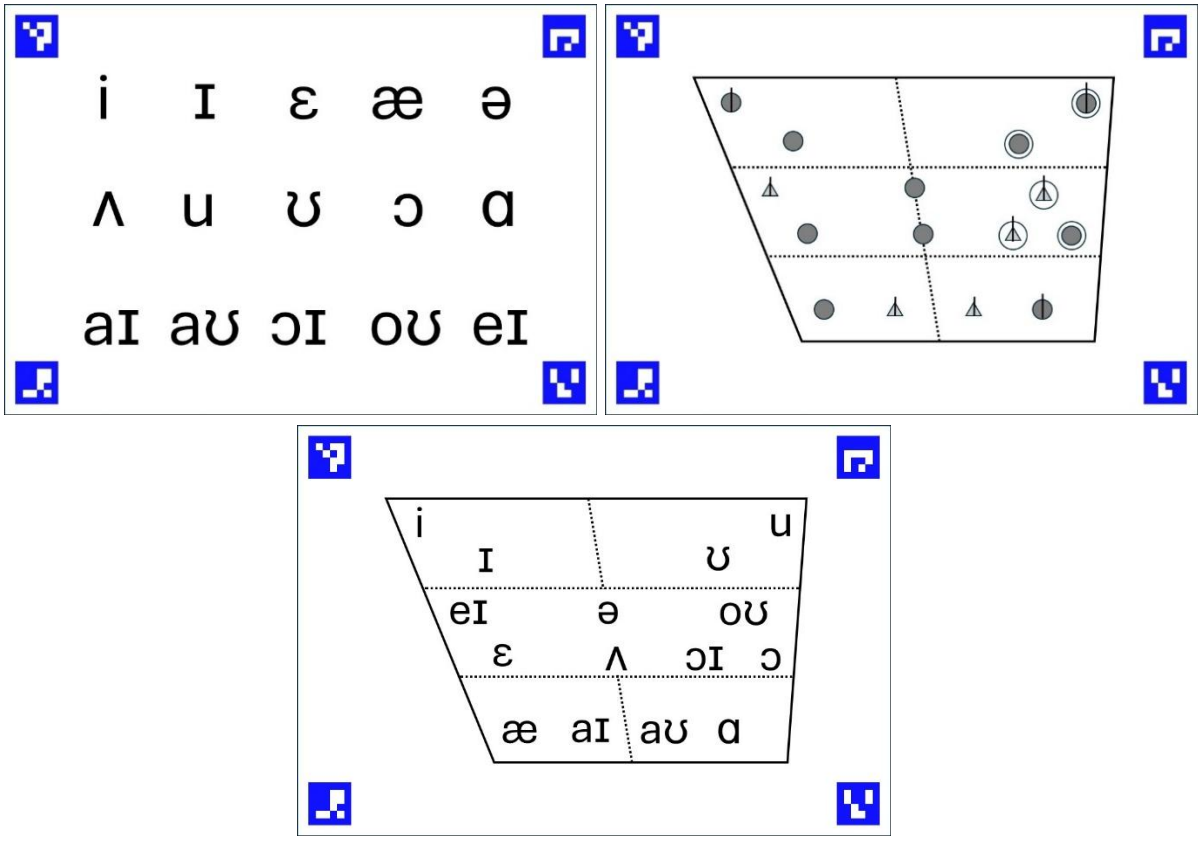


Figure 3 a - c: Three types of tactile sheets for learning IPA chart of vowels in modern American English with a) upper left, b) upper right and c) lower figure..

Results and Discussion

Although the number of participants was limited, the mean scores for all UEQ dimensions were positive (all scores > 1.1). The scores for "Attractiveness," "Dependability," and "Novelty" ranged from 1.6 to 1.8 and were higher than those for "Perspicuity" and "Efficiency." This trend indicates that participants evaluated the hedonic qualities of the system more positively than its pragmatic qualities. We attribute this tendency to the engaging nature of tactile-audio interaction, while learning the IPA chart itself posed a challenge for the participants. Indeed, both participants reported during the interviews that this was their first exposure to the IPA chart. Despite this novelty, participants indicated that the system was generally easy to understand and operate. Qualitative feedback further highlighted the system's usability and engagement. The male participant reported enjoying the process of predicting pronunciations based on tactile information before triggering the audio output and described the interaction as game-like. This suggests that the system encouraged active exploration rather than passive listening. Participants also provided constructive design suggestions. Specifically, they proposed introducing a dedicated tactile area for triggering audio playback, separate from the main IPA chart. In such a design, audio feedback could be activated by placing the non-dominant index finger on the designated area, rather than requiring simultaneous contact with both index fingers. By this comment, the system interface has changed after the evaluation.

Summary and Future Work

This paper presents a low-cost tactile IPA chart system with audio feedback to support visually impaired students in learning the construction and expression of English pronunciation. The system combines tactile sheets with a standard laptop and its webcam to provide immediate audio feedback based on finger positions. A preliminary evaluation with severe visually impaired students showed positive user experience ratings and indicated that the system was engaging, easy to use, and promoted active exploration. Although these results cannot demonstrate educational effectiveness because the evaluation was only for user experiences and the sample size was small, the fact that the system ability to receive immediate feedback on sound information by touching tactile materials is attractive to the learning process. Furthermore, the proposed system is affordable enough to be introduced in general schools. Therefore, in addition to developing more effective English and phonetic symbol learning materials, we would like to develop a system that allows teachers to create teaching materials more easily by themselves in the future.

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Development of Models for Anatomical Learning for the Visually Impaired: Skull Model, Ventricle and Brainstem Model, Eyeball Model

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Abstract

This paper reports the practice-oriented development of three tactile anatomical models for learners with visual impairment: a skull model, a ventricle and brainstem model, and an eyeball model. The models were created for anatomy classes at a school for the blind in collaboration with anatomy instructors. Shape data were designed in 3D-CAD and fabricated by fused-filament 3D printing. The main design challenges were to simplify anatomically complex forms for beginner-level tactile exploration, support repeated assembly and disassembly, and combine tactile cues with color cues for learners with low vision. The skull model was modularized into 22 bone parts and connected with magnets; the ventricle and brainstem model was simplified to improve tactile comprehensibility while preserving the overall structural relationship between parts; and the eyeball model was designed as a disassemblable model clarifying the layered structure of the sclera, choroid, retina, and major tissues. All three models were iteratively refined based on comments from anatomy instructors. The contribution of the paper is the clarification of design rationale and practical refinement points for tactile anatomical models rather than a controlled measurement of learning outcomes.

Keywords: Additive Manufacturing, Anatomy Education, Tactile 3D Model, Shape Simplification, Visual Impairment, Tactile Learning.

Introduction

For students with visual impairment, tactile graphics and 3D models are complementary rather than interchangeable learning media. Tactile maps and graphics remain essential for spatial access and symbolic representation [1-3, 14, 18], while digitally fabricated 3D models can convey volumetric, layered, and part-whole relationships that are difficult to communicate through 2D media alone [12, 15-17]. Recent reviews also show that accessible tactile media increasingly combine digital design, additive manufacturing, and multimodal interaction [17, 18].

In the ICCHP STS on tactile graphics and 3D models, a broad range of tactile teaching materials has been reported, including models of mathematical curved surfaces [5], enlarged plankton skeletons [6], heart models [7], Earth and globe models [8, 11], tabletop internal-organ models [9, 10], and interactive methods for obtaining layered verbal information from tactile graphics and 3D models [13]. These studies show that tactile learning is not achieved by geometric accuracy alone; educational usefulness also depends on scale, simplification, modularity, labeling, and the way learners explore and manipulate the model [12-17, 19, 20].

Anatomical learning poses a particularly demanding design problem because many structures are simultaneously complex, fragile, nested, and unfamiliar to beginners. Commercial anatomy models often reproduce medically faithful shapes, but this can make tactile exploration and assembly difficult for novice learners with visual impairment. In addition, blind and low-vision students may require different combinations of tactile, structural, and color cues [10, 14, 16]. Existing anatomical tactile models have

mainly addressed individual organs or whole-organ spatial arrangement [7-10], whereas there remains a practical need for models that support tactile understanding of segmented skull bones, the topological relation between ventricles and brainstem, and the layered structure of the eyeball.

This paper therefore presents a practice-oriented development report on three tactile anatomical models created for anatomy classes at a school for the blind: a skull model, a ventricle and brainstem model, and an eyeball model. The contribution is not a controlled educational study but a documented design process focused on three questions: how to simplify complex anatomy while preserving educationally important structure, how to support repeated assembly and disassembly, and how to make the models useful for blind, low-vision, and sighted learners in inclusive settings. By clarifying this scope and relating the work to prior tactile-model research, the paper aims to provide transferable design knowledge for future anatomical model development.

Development Process and Models

This study was initiated at the request of physical-therapy teachers at schools for the blind, who identified three anatomy topics for which existing materials were insufficient: skull bones, the ventricle and brainstem structure, and the eyeball. The development cycle was instructor-centered and iterative: curricular needs were discussed with the teachers, a prototype was designed in 3D-CAD, the prototype was fabricated by 3D printing, the teachers inspected it tactually and visually, and the geometry, joints, or color scheme were revised. Because this OAC paper documents practical development, the reported evaluation is limited to expert feedback from anatomy instructors; no formal user study with students or quantitative learning-outcome measurement was conducted within the scope of this paper. The common design criteria were tactile discriminability, ease of assembly/disassembly, anatomical interpretability for beginners, manufacturability, and usefulness for low-vision as well as blind learners. The key points in the development of each model are described below.

The Skull Model

A skull model consisting of 22 bone parts (8 cranial bones and 14 facial bones) was created (Fig. 1). Bone-shape data were obtained from Anatomography, a service for creating and displaying human anatomical diagrams. Important design considerations were modular connection with magnets, the use of different colors for adjacent bones, and simplification of the shape (e.g., making some asymmetrical features symmetrical). Life-size and twice-enlarged models were created. A total of 72 magnets were used.

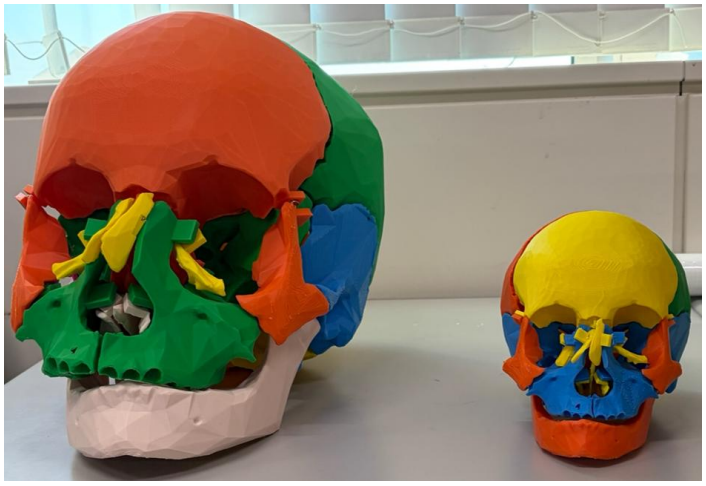


Figure 1: Left: a twice-enlarged model, right: a life-size model

The Ventricle and Brainstem Model

Commercially available models for learning the structure of the ventricles and brainstem can be disassembled into parts. However, because they almost completely fill the three-dimensional space, they are easy to disassemble but difficult to reassemble. In this study, a ventricle and brainstem model with a moderately simplified shape was created to make the overall structure more comprehensible by touch (Fig. 2).

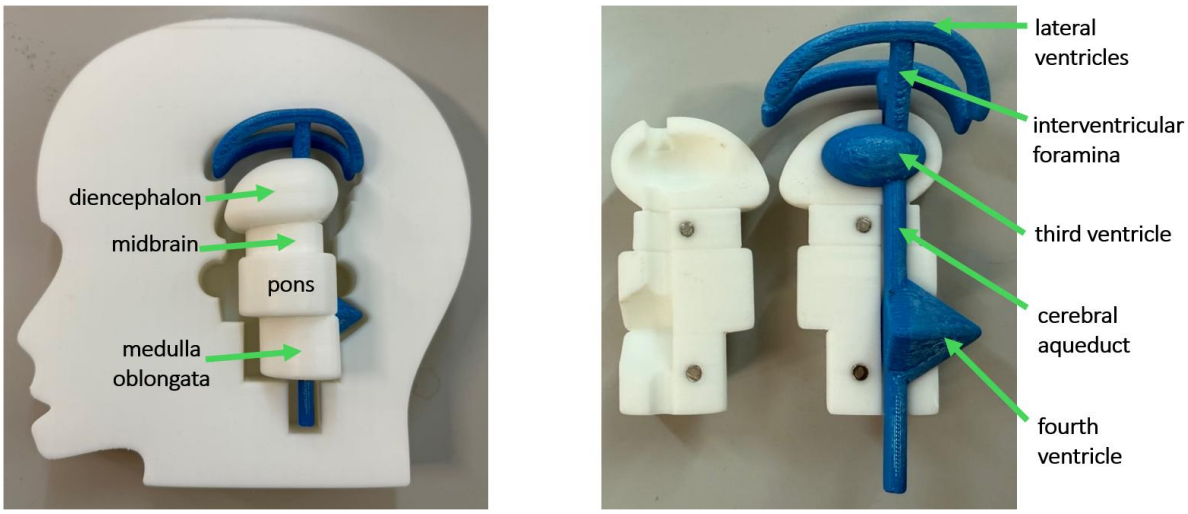


Figure 2: Left: Ventricles (blue area), brainstem (white area), white base (cross-section of the head), Right: Ventricles (blue area) and separated brainstem (white area)

The Eyeball Model

A disassemblable tactile model representing the basic structure of the eyeball was created (Fig. 3). The main design requirements were to represent the three-layer structure of the eyeball (sclera, choroid, and retina), the principal constituent tissues (cornea, iris, ciliary body, lens, optic disc, macular fovea, optic nerve, etc.), and good operability as a tactile model.

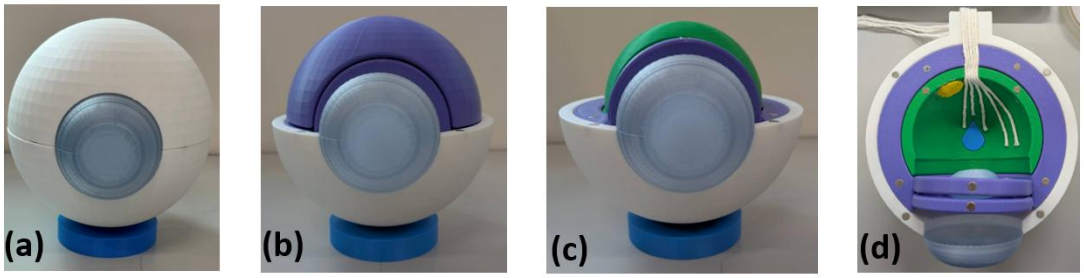


Figure 3: (a) Appearance of the eyeball model, (b) the model with the upper half of the sclera removed, (c) the model with the upper half of the choroid removed, (d) the model with the upper half of the retina removed (plan view)

Design and 3D Printing

Each model was designed using 3D-CAD software (Autodesk Fusion or Autodesk Inventor) according to the improvement policy described above. After design, the models were fabricated using Bambu Lab 3D printers based on fused filament fabrication (FFF). The filament material was polylactic acid (PLA) resin.

Iterative Refinement, Discussion, and Limitations

Anatomy instructors at schools for the blind inspected prototypes of the three models and suggested revisions mainly concerning palpation accessibility, assembly stability, and the degree of simplification. The resulting improvements and their implications are summarized below.

We created skull models at life size and twice life size. Because magnets could not be attached directly to some small bones, we attached them by adding rectangular prisms with magnet holes. However, some of these prisms interfered with palpation (e.g., in the nasal cavity). Therefore, their positions were shifted so that they did not interfere with tactile exploration.

Commercially available models of the ventricles and brainstem closely correspond to their actual shapes, but they are too complex to be used as palpable models for students learning anatomy for the first time. In this study, a major challenge was to simplify these complex shapes appropriately. This was achieved through multiple iterations of refinement based on comments from anatomy instructors at schools for the blind, leading to the final shape shown on the left side of Fig. 2.

In the prototype eye model, the ciliary body was adjacent to the retina in plan view. In the final version (Version 3), the iris and ciliary body were revised so that they became adjacent to the choroid, and the entire uvea (choroid, iris, and ciliary body) was unified in purple. This color coding is useful for students with low vision. Because the tactile models are universal models, they can also be useful for sighted students.

Compared with earlier internal-organ models [9, 10], the present study focuses on local anatomical structures and therefore required different simplification strategies. The skull model emphasizes part-whole segmentation and non-obstructive fixation between bones; the ventricle and brainstem model emphasizes topological comprehensibility of a highly complex three-dimensional space; and the eyeball model emphasizes sequential access to a layered internal structure. Across all three cases, the design process confirmed a recurring principle in tactile-model research: exact anatomical data alone do not guarantee educational usefulness, and task-specific simplification and interaction design are essential [11-17, 19, 20].

A limitation of the present paper is that user involvement in the reported design loop was mediated mainly through anatomy instructors. Although the models were used in classes, we do not report a structured user study with visually impaired students or measurable learning gains. Future work should therefore include direct student testing, task-based performance measures (e.g., identification accuracy, assembly time, and error patterns), retention measures, and possibly audio-linked labeling or point-and-tap access to explanatory information [13].

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Inclusive and Intelligent Digital Healthcare

Evaluating Healthcare Staff Perceptions of AI-Enabled Indoor Wayfinding Technologies

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Abstract

Healthcare facilities present complex indoor navigation challenges that disproportionately affect patients, visitors, and people with disabilities. Traditional wayfinding methods such as static signage, printed maps, and staff-guided assistance are inadequate for diverse accessibility needs and impose substantial operational burdens on healthcare workers. This study investigates hospital staff perspectives at Good Shepherd Rehabilitation Network (GSR) on current indoor wayfinding challenges and anticipated impacts of MABLE (Mapping for Accessible Built Environments), an AI-powered indoor navigation system. Using a cross-sectional survey (n = 135), staff across clinical, administrative, and support roles evaluated current navigation difficulties and impact of MABLE deployment. Findings reveal that approximately 40% of staff currently rate patient and visitor navigation as poor or unhelpful, with 55% assisting lost visitors one to two times per week, primarily by physically walking them to destinations. Over 80% of respondents reported being often or sometimes distracted from core duties by wayfinding demands. Following MABLE exposure via an explanatory video, staff expressed strong optimism: 70% anticipated navigation becoming easy or helpful, 55% expected fewer visitors to need assistance, 65% anticipated spending less time per interaction, and 60% predicted rarely or never being distracted. Over 80% of staff rated addressing wayfinding as important or very important, demonstrating broad organizational readiness. These results highlight significant unmet navigation needs in healthcare settings and support the potential of AI-powered assistive technology to reduce staff burden, improve visitor experience, and advance accessibility for people with disabilities.

Introduction

Healthcare facilities are among the most complex indoor environments, characterized by intricate layouts, multiple wings, unclear signage, and frequent renovations that alter spatial configurations. For people with disabilities, including those with visual, mobility, or cognitive impairments, these navigation challenges can create significant barriers to accessing healthcare services, attending appointments independently, and participating fully in treatment programs. The stress and anxiety associated with getting lost in medical environments can compound existing health concerns and discourage facility use [1, 2].

While outdoor GPS navigation has transformed wayfinding in exterior spaces, indoor environments lack comparable technological solutions. Traditional approaches such as static signage, printed maps, and human assistance remain dominant but prove inadequate for serving diverse accessibility needs [3, 4]. Staff members in healthcare facilities frequently interrupt their primary duties to provide wayfinding assistance, creating operational inefficiencies and potential delays in care delivery. The financial burden of ineffective wayfinding in healthcare is substantial: a survey of U.S. hospital staff estimated associated costs in the billions annually, encompassing staff time, patient dissatisfaction, and care delays [11]. These challenges are compounded by broader issues of missed appointments which alone cost the U.S. healthcare system approximately $150 billion annually [9, 10], with poor navigation representing one documented contributor to late arrivals and non-attendance [11].

Despite the scale of this problem, technological solutions for indoor wayfinding remain underdeveloped. Recent advances in artificial intelligence, robotics, and crowdsourcing technologies offer promising opportunities to address these challenges [5, 7, 8]. Mapping for Accessible Built Environments (MABLE) leverages AI-powered mapping, real-time updates, and personalized accessibility profiles to provide turn-by-turn navigation tailored to individual user needs [6]. Unlike conventional wayfinding solutions, MABLE emphasizes universal design principles, ensuring that the system serves people with and without disabilities through customizable routing that accounts for wheelchair accessibility, visual impairment accommodations, cognitive support needs, and emergency evacuation requirements.

This study investigates hospital staff perspectives at Good Shepherd Rehabilitation Network on current indoor wayfinding challenges and the anticipated impact of MABLE, an AI-powered wayfinding system, in mitigating these challenges. Staff are uniquely positioned to provide insights into visitor navigation difficulties, including those experienced by patients with disabilities and their families as they regularly assist those who are lost or confused [11]. This staff-centered approach complements existing end-user studies that have examined MABLE's potential from the perspectives of people with blindness, low vision, and mobility impairments [12-15].

Our Work

This research employs a cross-sectional survey design to assess staff perceptions of indoor wayfinding challenges at Good Shepherd Rehabilitation (GSR) and evaluate anticipated benefits of the MABLE wayfinding system. The study received institutional approval (Kansas State University IRB# 10616) and follows ethical guidelines for human subjects research, including informed consent procedures and voluntary participation protocols.

Participants and Recruitment

Participants include staff members across clinical, administrative, support, and operational roles at GSR, representing diverse perspectives on wayfinding challenges. Recruitment occurred through institutional email announcements and staff meetings, with voluntary participation incentivized through a gift card drawing. Participants can withdraw at any time without penalty, and survey responses are anonymized to protect confidentiality while maintaining data integrity for future research applications. A total of 135 responses were included in this study after removed duplicated responses. Data collection started in January 2026 and closed in February 2026.

Survey Instrument

The survey instrument using Qualtrics platform comprises of 21 questions organized into five themes: demographic information, technology usage patterns, current wayfinding experiences, visitor wayfinding support, and workplace impact and impact of technology interventions. Demographic questions assess education level, age, work hours, job role, and disability status to enable subgroup analysis. Technology questions explore smartphone platform usage and prior experience with wayfinding applications.

Core assessment questions employ Likert-scale matrices to evaluate current navigation ease and anticipated MABLE helpfulness across multiple dimensions including personal mobility in familiar and unfamiliar spaces, frustration and anxiety levels, staff perceptions about visitor navigation difficulties, workplace distractions, and incivility experiences resulting from wayfinding frustrations. Additional questions quantify assistance frequency, time expenditure per assistance episode, commonly requested destinations, and preferred assistance methods.

Once the challenges of wayfinding are identified, participants view an explanatory video demonstrating MABLE's functionality, ensuring informed evaluation of the system's anticipated impact. This approach

balances assessment of current challenges with forward-looking expectations for technology-mediated improvements.

Video conceptualization of MABLE

The "Welcome to MABLE!" video explains it is available as a web browser and a mobile app and will provide digital accessibility maps of indoor environments with interfaces for assessing, planning, and navigating within these environments based on the affordances and capabilities of the user. The technology stack behind MABLE is explained to leverage crowdsourcing, artificial intelligence, and robotics to automate indoor mapping and provide dynamic updates. The system is demonstrated through a prototype walkthrough at GSR and explained as being developed using a user-centered design approach informed by feedback from the BVI and MI community. The project's broader community impact is also emphasized, with support from the National Science Foundation's Convergence Accelerator Program and collaborations across research, accessibility, and disability advocacy groups.

Data Analysis

Quantitative data analysis employs descriptive statistics to characterize participant demographics, current wayfinding challenges, and assistance patterns. Comparative analysis examines differences between current navigation difficulty ratings and anticipated MABLE helpfulness ratings using paired comparison techniques. Subgroup analyses explore whether perceptions vary based on job role, disability status, prior navigation app experience, or other demographic factors.

Qualitative responses to open-ended questions undergo thematic analysis to identify common concerns, suggestions, and nuanced perspectives not captured by structured questions. Integration of quantitative metrics and qualitative insights provides comprehensive understanding of staff experiences and expectations.

Results

Patient and Visitor Navigation Ease

Staff perceptions of patient and visitor navigation ease revealed a pronounced gap between current conditions and anticipated improvements following MABLE implementation (n = 117–121). Currently, approximately 40% of staff characterized navigation as *poorly or not helpful*, while only a negligible proportion rated it as *easily or helpful.*

With MABLE, this pattern is expected to reverse substantially. Staff anticipate that the *easily/helpful* category will rise to approximately 70%, while the *poorly/not helpful* category is expected to decrease markedly.

Frequency of Assisting Lost Visitors

Survey respondents reported frequently assisting lost visitors in their current workflow (n = 127). The most common frequency was *1–2 times per week*, reported by approximately 55% of staff. Approximately 20% reported they didn't need to assist lost visitors, while a smaller proportion reported higher frequencies of 3–5 or more times per week.

Regarding expected changes following MABLE deployment, approximately 55% of staff anticipated that *fewer people* would need assistance. Roughly 10% were unsure, 10% expected no change, and a small minority (~5%) anticipated assisting *more people.*

Time Spent Assisting Each Person

Staff currently report spending predominantly *1–2 minutes* per person when providing wayfinding assistance (n = 104–127), with approximately 45% of respondents selecting this interval. Approximately 20% reported spending *under 1 minute* per person, while smaller proportions reported 3–5 minutes (~15%) or longer durations.

Looking ahead, approximately 65% of staff expected to spend *less time* per person following MABLE implementation, representing the dominant anticipated outcome. Roughly 20% were unsure, while very few expected *no change* or *more time.*

Most Common Locations Visitors Need Help Finding

Staff ranked the locations that visitors most frequently required assistance finding (n = 87; lower average rank = higher priority). Registration/Check-In and the Main Entrance/Lobby emerged as the top two highest-priority locations, each receiving average rank scores approaching 4. Restrooms and the Therapy Gym followed closely. Mid-tier destinations included Physician Groups/Offices and the Dining Area.

Patient/Resident Rooms and the Parking Garage/Lot were rated as lower-priority wayfinding needs, with average ranks closer to 6–7. Nurse Stations received the lowest priority ranking (highest average rank score), suggesting that visitors less commonly seek help finding this area.

How Staff Currently Assist Visitors with Wayfinding

Staff reported using multiple methods to assist visitors with wayfinding (n = 120; multi-select). The most common approach was *walking visitors to their destination*, selected by approximately 105 respondents. *Giving verbal directions* was nearly as common, with approximately 100 mentions.

Less frequently used methods included *pointing in the right direction* (~35 mentions), *using signage or wall maps* (~15 mentions), and *referring to a help desk/booth* (~12 mentions).

Work Distraction Due to Wayfinding

Survey respondents reported notable levels of work distraction stemming from wayfinding assistance duties (n = 101–107). Currently, approximately 55% of staff indicated being distracted *often* from core duties, approximately 40% *sometimes*, and only about 5% *rarely/not at all.*

Anticipated distraction in the *often* category is projected to drop to approximately 15%, while *sometimes* is expected to decrease to around 25% with MABLE. Notably, the *rarely/not at all* category is anticipated to increase to approximately 60%.

Perceived Importance of Addressing Wayfinding Issues

Staff expressed strong agreement on the importance of addressing indoor navigation challenges at the organizational level (n = 127). Approximately 47% of respondents rated this as Important and an additional ~35% rated it as Very Important, together accounting for over 80% of respondents. A small proportion rated the issue as Neutral (~12%), while Not Important and Not Very Important together accounted for fewer than 10% of responses.

These results reflect broad organizational buy-in for wayfinding improvements. The overwhelming majority of staff view indoor navigation as an issue worthy of attention, providing a strong foundation of support for MABLE deployment.

Conclusions and Possible Next Steps

This study investigates staff perspectives on indoor wayfinding challenges in healthcare facilities and evaluates anticipated impacts of AI-powered wayfinding technology. By examining the experiences of GSR staff who regularly assist lost visitors and patients, we document the scope of current navigation problems, their operational consequences, and expectations for technology-mediated improvements.

Future work will involve longitudinal assessment to determine whether anticipated benefits materialize in practice and identify unexpected consequences or adoption barriers. Further user studies with patients and visitors, particularly those with disabilities, testing MABLE installed in GSR will complement staff perspectives by directly examining navigation experiences and technology usability. End-user studies of receptiveness to emerging technology for indoor wayfinding such as MABLE, have already been conducted with people with blindness and low vision, and mobility challenges [12-15].

Additional research should investigate implementation strategies for healthcare facilities, including infrastructure requirements, training needs, privacy considerations, and cost-benefit analyses. Comparative studies across diverse healthcare settings including hospitals, outpatient clinics, long-term care facilities, and specialty practices would illuminate how architectural complexity, patient population characteristics, and organizational contexts shape navigation challenges and appropriate technological responses.

Ultimately, this research contributes to the broader goal of creating universally accessible built environments where people with disabilities can navigate independently, safely, and confidently. By understanding stakeholder perspectives and operational impacts, we can design and implement assistive technologies that meaningfully enhance accessibility while addressing real-world constraints and requirements.

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Care4Skills: Using Unusual Methods to Anticipate Emerging Skill Needs in the Long Time Care Sector

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Introduction

This contribution presents a novel approach to determining emerging skill needs in the longterm care (LTC) sector, using data mining and machine learning approaches.

For this, a web and server architecture was created to download relevant job listings from platforms that allow the processing of their data. Large Language Models were then used to automatically extract the skills discussed in the listings. The listings are analyzed in different ways: First, for ESCO-relevant skills, secondly, for specific digital skills, and finally, for certain digital tools the employers wish their staff to have knowledge of. The downloaded listings are also mapped geographically, which gives us the opportunity to draw careful preliminary conclusions about regional skill needs. It also allows us to map the tools used and the jobs geographically and come to conclusions about which tools (or how many different ones) are used in which regions.

All of this gathered data will then be used to create curricula and training materials that should help care personnel stay up to date in their jobs. At the point of writing, more than 2000 job listings related to Long Time Care Work have been gathered and evaluated to prove that the concept presented here is viable. The data collection has been restricted to German and French listings (because of the ease of access and language capabilities of the team), but, until the end of the project, a number of at least 15 000 job listings from multiple EU Countries, especially those countries from the consortium (as they will serve as a solid representation of the wider EU). These countries include Finland, Hungary, Bulgaria, Austria, Italy, Spain, Belgium, and more.

State of the Art

Eurostat is a European agency that collects various data points. They also publish statistics about jobs and employment, and they have a dedicated database about skills [1] related to these jobs. They derive their skills data (which skills are required in which occupation) through a series of surveys they conduct. This approach is very thorough, but takes a lot of time.

European Centre for the Development of Vocational Training [2] or Cedefop is another European agency dealing with skills in the job market. Their focus are statistics about abilities and reskilling- but they do not deal with these skills on a granular level. For example, they compare numbers of nursing school graduates in a country with the number of new jobs in that sector that arise. For their statistics, they get the raw data from Eurostat, which they process further.

ESCO [3] is a project that looks at which skills and competences are needed for which occupations, and they provide proper classifications of these qualifications. They work in a high granularity: For example, the page about social care workers lists tasks such as "apply organizational techniques", "listen actively", or "apply person-centered care" [4]. These skills can serve as a solid guideline for the approach presented here, giving us a list of skills that we can use as a blueprint for measurement. However, the data does not talk about the importance of skills over other skills in the real-world workforce. Also, this data is also the result of thorough surveying and expert analysis.

BeWell is an EU project similar to Care4Skills, in that it serves the purpose to up- and reskill the European health-care workforce [5]. For this, they also use courses and curricula, which are based on

their findings regarding skill needs in their discipline. To discover these skill needs, they also made professionals take surveys. The novelty of the approach presented in this submission comes from the fact that the data does not stem from self-reported surveys, but from a scientific process of looking at current real-world requirements in the workforce, through the analysis of requirements contained in real-world job listings. Creating and evaluating questionnaires takes time, but the process described here automates this process. Another novel aspect is the granularity and modularity of this data. It grants an insight into skills at a level that ESCO describes them, while also allowing us to look at new technologies that arise in real time. These skills and technologies can serve as a basis for further long-term care-centered curricula development and reskilling on qualifications that are current and useful.

Approaches

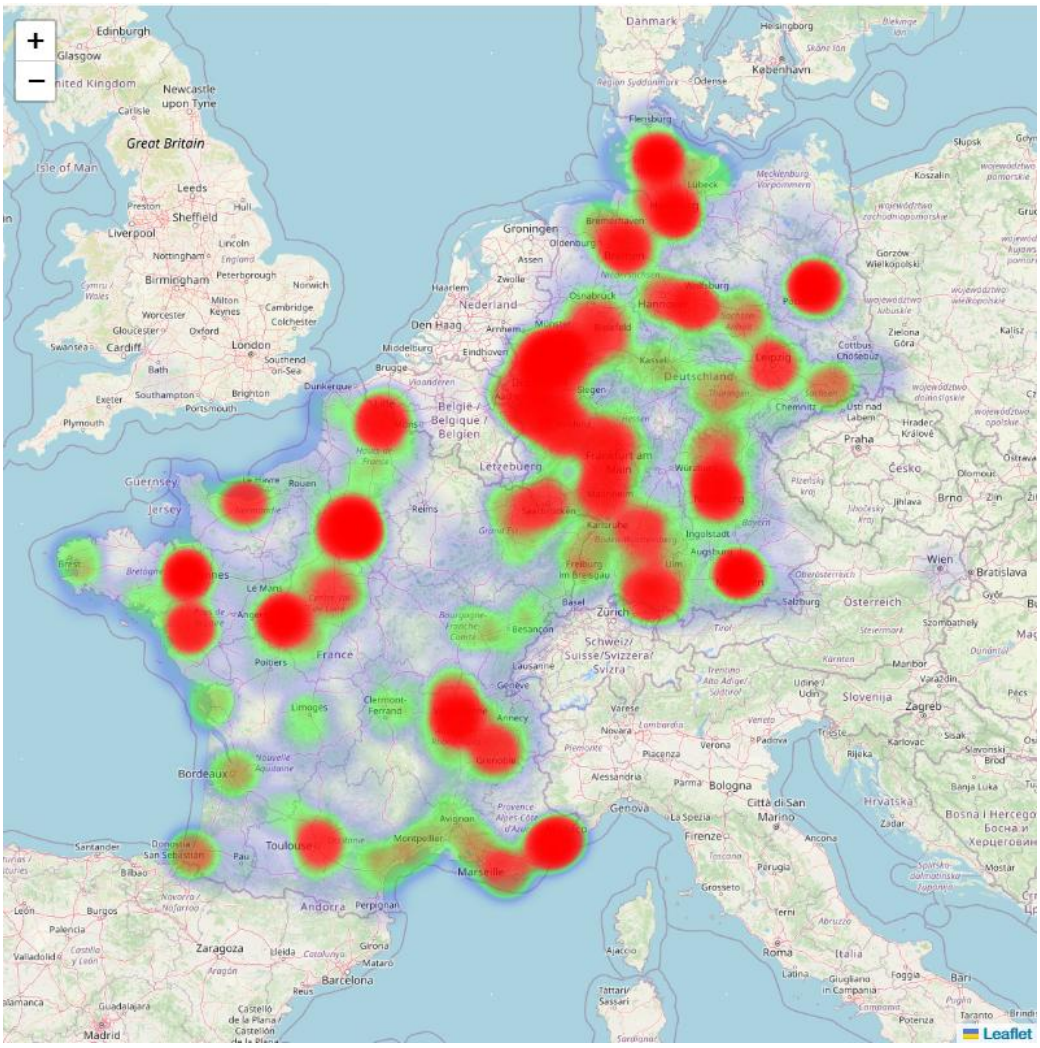


Figure 1: The Regional Distribution of Mined Jobs

Below, the step-by-step approach will be explained. It will be split into the **Data Gathering Phase** (Where job listings are mined), the **Skill Extraction Phase** (where an LLM is used to extract the skills from the listings) and the **Evaluation Phase**, which shows the preliminary results and how they were derived.

Data Gathering

To acquire specific job listings that are relevant to the long-term care sector, online job platforms were crawled. In Germany, there even exists an API database, provided by a central employment agency, which gives us access to this information fairly easily [6]. The data mining infrastructure built up in this

project basically allows us to enter a search term into a job platform and download all of the results related to the query. The individual results are then saved as HTML and stripped of unnecessary information to make the files easier to process later. A series of internal algorithms removes the tags and tries to leave only the text of the actual job listing, which, given that each platform is different, has a completely different architecture and way of "marking" where the text is stored. This means that the process has to be done very carefully, so as not to lose vital information. All of the data was saved, together with the date it was posted, the location specified, and the exact job title, which should preserve as many data points as possible for future analysis. Some platforms do not allow data mining, and the rules of their "robot.txt" [7] files (a file on each website that programmatically lays out the guidelines regarding data mining) were respected. The General Terms and Conditions were also consulted and respected. This gives us a smaller pool of possible listings, but allows us to stay on the right side of the law. For legal reasons (and out of respect for the platforms), no direct job listings will be published, and all information will be made public in aggregate form.

Skill Extraction

Next, the skills mentioned in the job listings (such as in the "Requirements" or similar sections) are extracted. For this task, Large Language Models are used (**gemma3:12b** [8]). This process is fickle and needs a lot of finetuning: The way the model reacts changes depending on a lot of factors, such as the prompt, the settings of the LLM (especially Temperature, Top P and Top K), and the size of the model. Here, a balance has to be struck between accuracy and speed: Because we have a large set of data and run the process thousands of times, we want something fast, while remaining accurate enough to make a useful prediction. A serious concern regarding the data extraction capabilities of LLMs are hallucinations [9]. LLMs sometimes report data with the highest confidence that (sadly) is absolutely not true. At this point, most people have one or more (most likely: a lot) of personal anecdotes regarding models like ChatGPT or Claude blatantly lying to them. These lies are called "hallucinations" and they would massively distort the outcomes of this study if left unsupervised. A few countermeasures were set in place: As argued in [9], the models start lying if they are not sure about an outcome (meaning they start to guess)- so part of the instruction they received included a specific "write x if there are no skills mentioned or if you are not sure". This should make it write the "x" instead of hallucinating. The cited paper does not include a statistic if an approach like this would solve the issue of hallucination in general, but the manual testing that was done (looking at 30 listings and comparing them with the LLMs output) proved that this approach is viable. In almost all examples (28 out of 30) the output only included skills that where mentioned in the job listings. In the cases where an issue occurred, the LLM did not follow its instructions correctly and instead replied with a translated text. Mistakes like this are sorted out through an algorithm and do not affect the final evaluation. To further ensure the success of this approach, the same data is put into the LLM a second time.
The output is fed back into the system, together with instructions and the original text. If the model does not confirm the conclusion that the other model came to, the output is discarded. This approach was used to extract multiple data points. First, mentions of skills (matching the ESCO dataset) were extracted. Secondly, which digital skills were mentioned, and lastly, which specific technology is required of the job seeker.

Evaluation

The way these skills are mentioned in the listings can vary a great deal, which makes it hard to count absolute occurrences as an evaluation strategy. An example: The skills related to digital technologies can be called "digital skills" or "competence with a computer" in the job listings, even though they allude to the same essential skill. This problem was dealt with by encoding the skills into Word-Vectors, which are multi-dimensional mathematical representations of linguistic content. The word-vector for "competence with a computer" and "digital skills" are very close, as they have a similar semantic

meaning [10]. Encoding all of the mentioned skills into these vectors gives us the opportunity to extract clusters of vectors that lie close together.

For this, the Sentence Transformer **paraphrase-multilingual-mpnet-base-v2** [11] was used, which provides a 768 dimensional encoding.

At the moment, just the output of the LLMs is taken and processed, and the Clusters are calculated by proximity to each other. The algorithm used is **HDBSCAN** [12]**.**

In the future, we want to use the skills mentioned by ESCO as a basis for the clusters, with the vector distance to them constituting the cluster they will be sorted into. Items in the clusters that the system outputs now do in fact have semantic relations to each other, but the label has to be manually given by inspecting which skills were grouped together. For the digital skills evaluation, the three biggest clusters look like this:

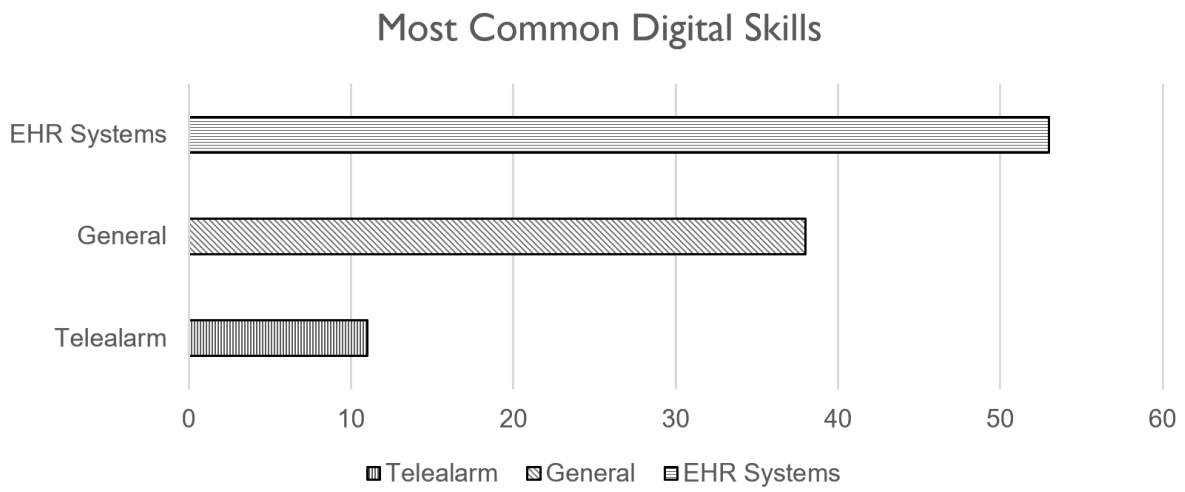


Figure 2: Here, the most Common Digital Skills are listed

EHR stands for "Electronic Health Records", meaning the ability to use software that displays patient info. The second largest cluster was titled "General", because it grouped together various digital capabilities, such as "Outlook" or "Word". The cluster titled "Telealarm" concerns itself with various patient-alarm systems that allow clients to call for help if they need it.

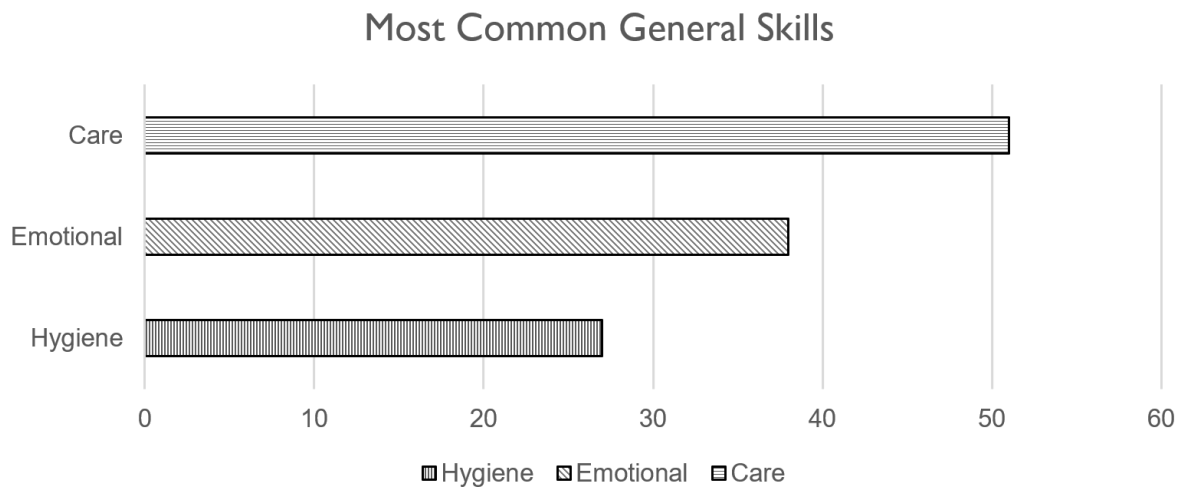


Figure 3: This figure shows the most common general skills which were included in the listings

The "Care" cluster relates to skills that are synonymous with being good at "care" - the cluster we termed "Emotional" describes skills such as "Emotional Durability" or "Resilience" and things of this nature- While the "Hygiene" Cluster contains skills that relate to patient hygiene and cleanliness.

Discussion and Future Work

At this point, every position that can be counted as a "care worker" is included in the data presented here, meaning that there has been no difference made between a home carer, someone caring for the elderly, or someone caring for people with a disability. A full analysis of the differences between the skills required for each will be done in by the end of the project, but has been ignored, because the dataset gathered so far is too small to draw any solid and statistically significant conclusions about fine-grained information like this. As discussed, the dataset will be enlarged significantly (nearly 10 times the size it is now). More countries will be represented too, to get a better picture of regional differences in skill needs.

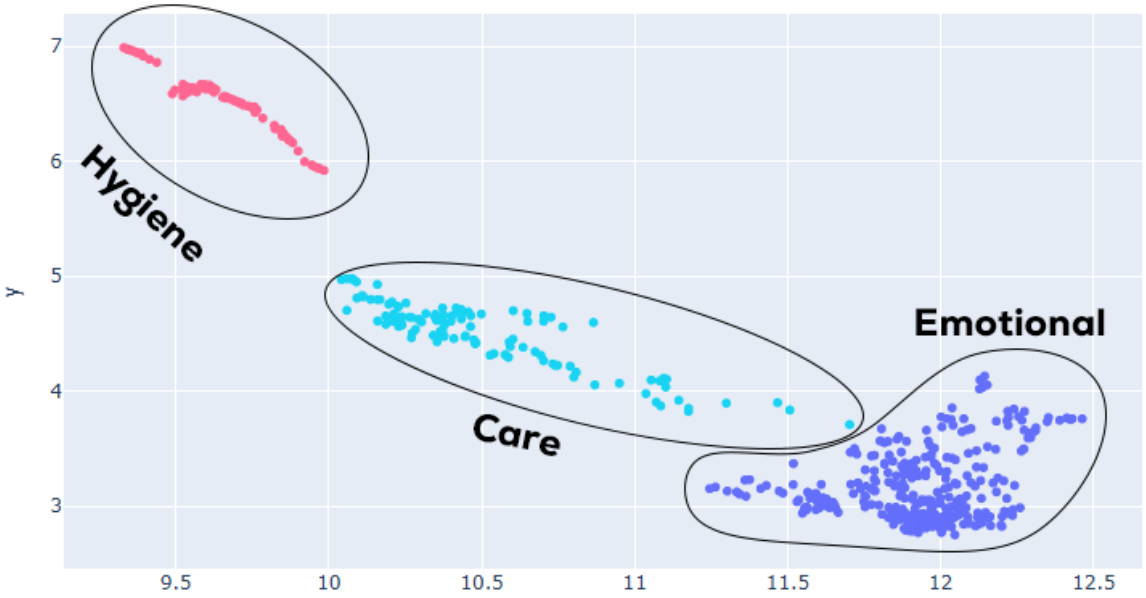


Figure 4: This picture shows the regional clustering of skills.

Also, a higher number of data points means a higher certainty when it comes to predicting skill needs. In addition, the skill extraction process will be reworked, with a more detailed evaluation and documentation of the LLM's accuracy. Also, RAGs [13] (retrieval augmented systems) will be evaluated in comparison to, to further reduce the "noise" created by the LLMs' output. In the evaluation, a comparison between naturally occurring clusters and those that use ESCO skills as a basis will be made. Using ESCO skills gives a more scientific basis (because the skills have been manually grouped by experts), while not restricting the clustering allows more recent developments in the job market to arrive naturally.

Acknowledgements

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Bridging the Support Gap: A Digital Mindfulness and Peer-Support Ecosystem for Parents of Children with Autism in Poland

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Abstract

Autism Spectrum Disorder (ASD) is a growing public health and social challenge, with the number of diagnoses increasing rapidly in recent years. Despite the expansion of child-focused therapeutic and educational services, the psychological needs of parents and primary caregivers remain insufficiently addressed. Research consistently indicates that parents of children with ASD experience elevated levels of chronic stress, anxiety, depression, and caregiver burnout, caused both by the daily demands of caregiving and by systemic barriers such as limited respite care, fragmented services, and social stigma. This paper examines the limitations of current "care-as-usual" models and proposes a conceptual framework for a mobile application designed to strengthen parental well-being through an accessible, non-clinical form of digital support. The app framework was developed based on the author's original qualitative research conducted with parents of children with ASD.

Introduction

Autism Spectrum Disorder is a complex neurodevelopmental condition characterized by persistent deficits in social communication and restricted, repetitive patterns of behavior. The global prevalence of ASD is rising, with current World Health Organization estimates suggesting it affects approximately 1 in 100 children [1]. In Poland, this trend is clearly visible; between 2012 and 2023, the number of ASD diagnoses rose from 18,924 to 131,440, and in the 2022/2023 school year alone, the number of children with special educational needs due to ASD increased by 30% [2]. While the medical and educational sectors focus heavily on the developmental outcomes of the child, the mental health of the primary caregivers is frequently overlooked. The public support system for ASD in Poland is often inefficient, leaving families reliant on NGOs and private initiative rather than a coordinated state strategy [3]. Research consistently demonstrates that parents of children with ASD experience significantly higher levels of stress compared to parents of typically developing children or those with other disabilities [4]. This stress is often chronic and cumulative, stemming not only from the direct demands of caregiving – such as managing aggressive behaviors or sleep disturbances – but also from systemic failures, including a lack of respite care and social stigma [5]. The consequences of unaddressed parental stress are extensive. Parents are at high risk for "caregiver burnout," depression, and anxiety [6]. Crucially, parental distress negatively impacts the child's prognosis; high stress levels in parents can reduce the effectiveness of behavioral interventions for the child [7]. Therefore, supporting the parent is not merely an act of compassion, but a necessity for the entire family system. This paper pursues two related objectives: first, to identify the specific psychological and contextual stressors experienced by Polish mothers of children with ASD through original qualitative research; and second, to translate these findings into evidence-based design requirements for a mobile application providing accessible, non-clinical wellbeing support.

State of the Art and Problem Statement

The Limitations of "Care-as-Usual"

Current support systems for families with ASD are predominantly child-centric. "Care-as-usual" typically involves logistical support (e.g., speech therapy, occupational therapy) which, while beneficial for

the child, does not address the psychological burden of the parent. When parents do receive training, it is often "parent implementation" training teaching them how to be co-therapists rather than "parent support" focused on their own wellbeing. While these programs increase parenting competence, they often fail to reduce psychological distress and can inadvertently increase the burden of responsibility [8].

The Role of Social Support and Isolation

Social support is a critical, yet frequently undervalued, pillar of parental well-being. Emotional support – most often received from friends and family – is the highest-rated form of help and correlates most strongly with relationship satisfaction [9]. However, parents of children with ASD often experience social withdrawal due to stigma. In this context, peer support becomes a vital mechanism for resilience. Support groups provide "validation of experience" and "normalization of difficulties" [10]. Contact with other parents allows caregivers to understand that their challenges are not isolated failures but shared systemic realities. This realization builds a sense of community that significantly reduces psychological isolation.

Mindful Parenting

Mindfulness, defined as the intentional, non-judgmental attention to the present moment, offers a mechanism to disrupt the cycle of parental stress. The model of "Mindful Parenting" extends this practice into the parent-child relationship through five dimensions: listening with full attention, non-judgmental acceptance of self and child, emotional awareness, self-regulation, and compassion [11]. In the context of ASD, mindfulness allows parents to shift from "automatic reactivity" (e.g., aggression during a meltdown) to "conscious responsiveness". Research indicates that this shift not only reduces parental stress but also correlates with a reduction in the child's aggression and externalizing behaviors [12]. However, traditional mindfulness courses are often lengthy, expensive, and require fixed attendance, making them inaccessible to caregivers with unpredictable schedules.

Digital Interventions

The digital delivery of mental health support offers a solution to the barriers of time and location. Asynchronous interventions allow parents to engage with therapeutic content at their own pace, a critical feature for caregivers with unpredictable schedules. While general mindfulness apps (e.g., Headspace) are popular, literature suggests that interventions are most effective when "tailor-made" for the target population, addressing their specific stressors and integrating community components to reduce isolation [13]. A mobile application differs significantly from traditional support groups for parents of children with disabilities. Above all, a tool designed to deal with chronic stress and problems connected to raising a child with intellectual disability must be tailored to a specific target group - in this case, specifically parents of children with autism. Support groups, especially in smaller towns, tend to cater to a broad range of individuals and issues related to various disabilities. Furthermore, these groups often consist of parents who are also at the beginning of their journey and lack extensive experience.

Proposed Conceptual Model

Based on a synthesis of literature, this project proposes a mobile application framework grounded in User-Centered Design (UCD). The proposed model integrates three core pillars: Asynchronicity, Self-Compassion, and Community Validation.

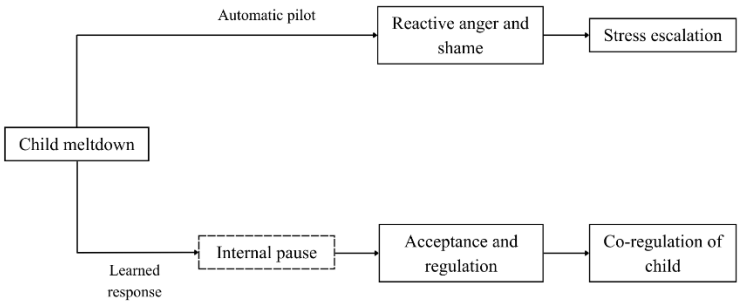


Figure 1: The Mechanism of Mindful Parenting. A flow chart comparing two parental responses to a child's meltdown: the "automatic pilot" path leading to reactive anger and stress escalation and the "learned response" path where an internal pause leads to acceptance and co-regulation. The diagram illustrates how mindfulness training creates an internal buffer between stimulus and response (based on Duncan et al., 2009).

Pillar 1: Asynchronous Micro-Interventions

Given that parents of children with ASD often lack large blocks of free time, the application must operate on an asynchronous model. Unlike traditional therapy or live webinars, the content must be broken down into "micro-interventions" – short, bite-sized exercises (e.g., 3-5 minutes) that can be accessed during brief moments of respite. This structure addresses the barrier of "time poverty" and prevents intervention from becoming an additional burden.

- Design Requirement: Content is delivered in "micro-doses" (3–5 minutes).
- Strategy: Instead of 45-minute body scans, the app offers "emergency pause" buttons and short breathing spaces designed to be used during or immediately after a stressful event. This approach targets the parent's "self-regulation in the parenting relationship"

Pillar 2: Self-Compassion as a Buffer

While mindfulness builds awareness, Self-Compassion builds resilience against guilt. Research [12, 14] indicates that self-compassion is a stronger predictor of parental wellbeing than the severity of the child's autism symptoms. Design Requirement: Content is delivered in "micro-doses" (3–5 minutes).

- Design Requirement: The app must explicitly target the "inner critic".
- Strategy: Exercises will focus on "Common Humanity" – reminding parents that their struggles are not failures, but shared experiences. This differentiates the tool from standard parenting apps that focus on "skill acquisition," which can induce guilt when strategies fail.

Pillar 3: Peer-Validated Community (The Village)

Isolation is a key stressor for parents. General social media can be a source of judgment, whereas specialized communities (like the r/Autism Parenting subreddit) provide validation.

- Design Requirement: A moderated, text-based feed for sharing hardships ("venting") and small victories.
- Strategy: The community feature serves to normalize the unique challenges of ASD (e.g., public meltdowns), reducing the stigma and shame that often lead to social withdrawal.

Scope of Intervention: Support vs. Therapy

It is important to delineate the scope of this proposed tool. The application is conceptualized as a non-clinical support resource, such as commercial wellness platforms like Headspace or Calm, rather than a certified therapeutic medical device. It is not intended to replace professional psychotherapy or pharmaceutical treatment. Instead, it serves as an easily accessible, "first-line" support system. Its

primary goal is preventive: to reduce daily stress accumulation and provide immediate coping strategies for parents who may otherwise have no access to professional help due to the barriers previously described.

Methodology for Prototype Development

This paper presents the theoretical groundwork for a research project aimed at developing a prototype mobile application. The project adopts a User-Centered Design (UCD) approach.

Participants

The research group consisted of 18 volunteers, all of whom were mothers of at least one child diagnosed with ASD. Some participants also had additional children with other mental disabilities. The group was diverse in terms of age and place of residence. All participants received clear and comprehensive information regarding the study's aims and procedures. Informed verbal consent was obtained from each participant, confirming that involvement was entirely voluntary and that they maintained the right to withdraw at any stage. For participants who were unable to meet for an in-person interview or who preferred a digital format, a questionnaire was distributed. This questionnaire was developed for the study based on the Individual In-Depth Interview (IDI) script.

Data Collection and Analysis

The research design utilizes in-depth, semi-structured interviews. The interview protocol was designed to explore three key domains:

1. Stress Mapping: identifying specific daily triggers and current coping mechanisms (adaptive vs. maladaptive).
2. Digital Habits: understanding how parents currently use technology for support and what barriers exist to using current mental health apps.
3. Content Preferences: determining the preferred format of interventions (e.g., audio length, tone, community features).

Data will be analyzed using Interpretative Phenomenological Analysis (IPA) to inform the specific UX/UI requirements of the application.

Results

Analysis of the combined dataset, conducted using Interpretative Phenomenological Analysis (IPA), revealed five recurring themes that directly inform the application's design requirements.

Theme 1: Time Poverty and the Micro-Window

No participant reported having sustained blocks of time available for self-care. Available coping strategies were uniformly brief and opportunistic: a five-minute exit from the home, stepping into a separate room, or – in the case of a single mother working full-time – the daily bath as the only moment of solitude. When asked directly, most participants reported fewer than 30 minutes of daily recovery time, with 2 describing having almost none. This pattern directly operationalizes the "time poverty" barrier identified in the literature [13] and confirms that the application must function in micro-windows of 1–5 minutes rather than as a scheduled practice.

Theme 2: Daily Stress Peaks – Mornings and After-School Returns

Stress did not distribute evenly across the day. Two consistent high-stress windows emerged across the sample, independent of child age or family structure. Mornings: involving medication routines, rigid behavioral rituals, and transition preparation were described as among the most demanding moments

of the day by most participants. The after-school return constituted a distinct second peak, characterized by emotional unpredictability: parents consistently described not knowing "in what mood the child will come home" as itself a primary source of anxiety, regardless of what happened upon arrival. Situations in public spaces emerged as a third recurring trigger, particularly when the child's behavior drew commentary or judgmental reactions from strangers. These findings suggest that delivering short, targeted support before these predictable stress windows (rather than only in response to crisis) could meaningfully reduce daily burden.

Theme 3: Embodied Regulation and Informal Mindfulness Practice

A noteworthy pattern emerged when comparing participants' stated familiarity with mindfulness against their spontaneously reported coping behaviors. A substantial proportion of participants described mindfulness as unfamiliar or unsuited to them yet the strategies they relied on most naturally corresponded directly to what mindfulness-based programs classify as informal practice: deliberate breathing, brief physical separation from the stressful environment, and sensory grounding through music, gardening, or physical movement [11]. The somatic dimension of these strategies was particularly consistent. Participants reached instinctively for bodily regulation first, whether through walking, exercise, a bath, or tending to plants, without framing these behaviors in psychological terms. One participant articulated the underlying principle independently, describing mindfulness as having "many forms," including any situation that "forces you to be here and now." This gap between self-reported unfamiliarity with the concept and demonstrated practice of its constituent behaviors carries a direct design implication: the application should avoid mindfulness branding at the interface level, instead framing its tools as extensions of coping strategies the user already employs including short movement-based or body-anchored exercises alongside conventional breathing techniques.

Theme 4: Self-Critical Cognition Focused on Emotion, Not Action

All participants described a consistent pattern of self-directed criticism focused on their own emotional reactions to the child's behavior. Critically, the specific content of this self-criticism reveals a telling pattern: guilt was directed almost exclusively at emotional states rather than at actions or decisions – losing patience, raising their voice, failing to remain calm. Characteristic formulations included "I have no control over my emotions", "I am weak", and "A mother will always look for fault in herself". Self-compassion interventions in the application should not frame parental guilt in terms of behavioral errors or missed opportunities; they should explicitly normalize the experience of feeling angry, exhausted, and overwhelmed as a natural physiological and psychological response to an objectively demanding situation. The target is the emotional inner critic, not the parenting decision-maker.

Theme 5: Social Stigma and the Failure of Existing Community Formats

All participants reported exposure to unsolicited commentary and judgmental observation during public behavioral episodes, with recurring formulations such as "How did you raise this child?" and "What are you doing to that child?". One participant drew an explicit cross-cultural contrast, noting that an identical behavioral episode elicited no social response in England but prompted staring and commentary in Poland pointing to low neurodiversity literacy in the local social environment as the primary driver of stigma, rather than the child's behavior itself. At the network level, most participants receive meaningful and genuine support from the closest family. Some participants described a persistent sense of not being fully understood even by close friends or family by having someone to talk to but lacking genuine validation of their specific experience. Participants who had sought community in existing digital formats described abandoning them: Facebook support groups drifted into political arguments or interpersonal conflict, and a single harmful interaction was sufficient to permanently foreclose that channel for some. These failure modes together specify both the need for a dedicated peer community and the structural constraints it must meet single-topic scope, active moderation, and anonymous contribution as a default.

User Archetypes

Cross-analysis of the data yields three user archetypes relevant to design, summarized in Table 2.

Table 1: User archetypes derived from research data

	Reflective Self-Manager	Exhausted Isolate	Experienced Adapter
Support network	Strong	Weak or absent	Offline, established
Mindfulness familiarity	Prior exposure, positive	Limited or skeptical	None or indifferent
Primary need	Reflection tools, pattern recognition	Peer validation, common humanity	Practical information, low demand
Drop-off risk	Content too shallow	No immediate value on first use	Perceived intrusiveness

Design Implications

The five themes map onto four design requirements for the proposed application.

First, the data reveal that stress follows a predictable daily rhythm: mornings and after-school returns emerged consistently as peak burden windows across the sample. This suggests that the application should offer a high degree of personalization, allowing users to configure when and how they receive support based on their own daily patterns. Rather than generic scheduled reminders, the tool should adapt to the individual user's rhythm, positioning itself as a responsive companion rather than a one-size-fits-all wellness product.

Second, the application's primary screen state must provide single-tap access to a regulation tool usable within 60–90 seconds, without login barriers or navigation overhead. Given that participants already reach instinctively for embodied regulation strategies, this toolset should extend beyond breathing exercises to include short movement-based prompts e.g. a brief walk, a body scan anchored in physical sensation, or a grounding exercise using the immediate sensory environment. This feature extends existing coping behavior rather than introducing a new practice. Critically, none of these tools should be labelled "mindfulness" in the interface: most participants familiar with the term considered it unsuited to them, while simultaneously practicing its constituent behaviors intuitively. Framing the tools as extensions of what the user already does naturally is both more accurate and less likely to trigger disengagement.

Third, self-compassion content must be embedded in the post-crisis flow and precisely targeted at emotional, not behavioral, self-criticism. Following each regulation exercise, a brief normalizing message should frame the user's anger or exhaustion as a shared, physiologically grounded response to an objectively difficult situation – not as a parenting failure. The target is specifically the emotional inner critic, as opposed to the parenting decision-maker.

Fourth, the peer community feature must be structurally differentiated from the digital formats participants abandoned. A closed, single-topic, text-based feed with active moderation and anonymous contribution by default directly addresses the documented failure modes of existing community spaces. The feature must be opt-in and positioned as secondary to individual regulation tools. Unlike unmoderated self-help groups, topical safety is encoded in the architecture rather than dependent on community self-governance.

Beyond these core pillars, participants themselves proposed several additional features worth noting. One IDI participant suggested an AI-based assistant trained specifically on ASD-related cases and reliable sources, capable of responding to real-time questions about the child's behavior. Several participants expressed interest in an emotion and behavior diary (a tool for tracking patterns between parental emotional states and child behavior, enabling causal reflection over time). Others requested a curated, reviewable directory of verified therapeutic services, as well as accessible explanations of legal

entitlements and welfare benefits available to families of children with ASD in Poland. These proposals, generated organically by participants, point toward a modular application architecture in which core wellbeing tools are complemented by practical informational resources recognizing that for some users access to reliable specialist contacts or legal guidance may represent a more immediate need than mindfulness-adjacent content.

Discussion and Expected Impact

The proposed application addresses a gap that is simultaneously clinical, systemic, and cultural. In Poland, the absence of a coordinated state strategy for ASD family support leaves caregivers reliant on NGOs and private initiative [3], and general mindfulness applications have been shown to be significantly less effective for this population than tailor-made interventions [13]. A smartphone-accessible tool requires no appointment, no travel, and no fixed schedule. Given that parental stress directly reduces the effectiveness of behavioral interventions for the child [7], improving caregiver wellbeing is not only a welfare outcome but a clinical one. Implementation could be pursued through partnerships with ASD-focused NGOs or integration into diagnostic pathways at the point of diagnosis. Future research should focus on usability testing of a functional prototype with the target population, followed by longitudinal studies examining whether sustained use reduces parental stress. Extending the sample to include fathers and rural participants would further strengthen the generalizability of the findings.

Limitations

The sample consists exclusively of mothers, leaving fathers' experiences unrepresented. The sample size, while appropriate for qualitative inquiry, limits transferability. Participants were self-selected volunteers, introducing the possibility of response bias toward individuals who are more motivated to seek support or more comfortable discussing psychological distress. As a non-clinical tool, the application is unsuitable for parents experiencing clinical levels of distress and must clearly signpost professional services. Finally, as the Experienced Adapter archetype illustrates, a meaningful proportion of the target group may not engage with a digital tool regardless of its design the application is best understood as one component of a broader support ecosystem rather than a comprehensive solution.

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Health for All: Digital Health Literacy and Ethics as Foundations for Sustainable Digital Health Solutions

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Abstract

Digital health technologies offer significant potential to support health, autonomy, and independent living; however, their integration into everyday healthcare remains limited. This paper presents an integrated approach to enhance digital health literacy, technology acceptance, and ethical reflection, based on findings from multiple interdisciplinary research projects in the fields of telehealth, assistive technologies, and accessible healthcare.

Using a human-centered and participatory design framework, qualitative and quantitative data were collected across several projects involving diverse stakeholder groups, including patients, informal caregivers, and healthcare professionals. Key findings highlight a persistent gap between perceived usefulness and actual use of digital health technologies. While technology affinity and usability ratings were generally high, adoption was hindered by limited digital health literacy, insufficient technological competencies, and contextual as well as socio-cultural factors. For example, digital competence and routine device use significantly influenced suitability for telerehabilitation, while environmental conditions and diversity-related factors shaped acceptance in assistive technology contexts.

To address these barriers, three interlinked components were developed: (1) a Digital Health Lab as an experiential learning environment, (2) a modular Digital Health Literacy Training Concept, and (3) an "Ethics as Opportunity" card set to support structured ethical reflection. Together, these components aim to bridge the gap between acceptance and sustained use by targeting individual competencies, contextual fit, and inclusive design.

The findings suggest that digital health adoption should be understood as a multidimensional process shaped by the interaction of skills, environment, and socio-technical factors. Future research should evaluate the long-term impact of these interventions in real-world settings.

Introduction

Digital health technologies and assistive systems hold substantial potential to promote health, autonomy, and independent living across diverse population groups, especially the elderly and people with disabilities. Smartphones, wearable devices, and assistive technologies can support self-management, prevention, and safety in everyday life. Despite this potential, the systematic use of such technologies in healthcare and daily living contexts remains limited [1].

A central reason for this gap is insufficient digital health literacy among both potential users and healthcare professionals [2]. In addition, limited awareness of available technologies, concerns related to data protection, ethical implications, and lack of practical knowledge hinder adoption. Previous research indicates that healthcare professionals often lack structured opportunities to critically assess and integrate digital health technologies into their professional practice, which further impedes implementation[3].

Existing literature consistently highlights the barriers to adoption of assistive and digital health technologies. Meta-syntheses and empirical studies identify limited digital competencies, lack of training, and uncertainty regarding ethical and legal implications as major obstacles for both users and healthcare

professionals (e.g in [4], [5], [6]). Data privacy concerns and insufficient confidence in evaluating technological solutions further contribute to low uptake.

Training deficits among healthcare professionals have been identified as a critical factor. Recent studies emphasize that without targeted education and continuous professional development, digital health technologies remain underutilized despite their proven benefits [4]. At the same time, models of digital health literacy stress the importance of combining technical skills with critical evaluation, ethical awareness, and contextual understanding [7].

Human-Centered Design (HCD) [8] has emerged as a widely accepted framework for developing user-oriented digital solutions. By involving stakeholders throughout the design process, HCD enhances usability, acceptance, and relevance. Furthermore, technology acceptance models [9], [10], [11] underline the role of perceived usefulness, ease of use, and trust as decisive factors influencing adoption. In the digital health domain, health-specific extensions of the Technology Acceptance Model, such as the Health Information Technology Acceptance Model [12], demonstrate that these core constructs remain central while additional factors including system reliability, self-efficacy, and trust-related beliefs further shape users' attitudes and behavioral intentions towards health technologies. Furthermore, ethical reflection is increasingly recognized as an integral component of digital health innovation. Rather than treating ethics solely as a regulatory constraint, recent approaches frame ethical considerations as a driver for quality, inclusiveness, and long-term sustainability.

This paper presents an integrated approach that combines experiential learning, digital health literacy training, and ethical reflection. Based on insights from multiple applied research projects, a Digital Health Lab (DHL) and a complementary training concept were developed, supported by an ethical reflection tool ("Ethics as Opportunity" card set). The overall aim is to enhance acceptance, responsible use, and the sustainable integration of digital health solutions in both professional and private contexts to support health, autonomy, and well-being.

Methods

The presented approach is grounded in findings from several interdisciplinary research projects in the fields of accessible healthcare, digital health, assistive technologies, and telehealth (Interreg SI-AT projects Health for All and REHA2030; Interreg IT-AT project SENSHome; FFG projects TeleCareHub, iLead and PROTEA). These projects employed multimethod and participatory research designs, including workshops, semi-structured interviews, and field tests with diverse stakeholder groups.

All empirical activities were guided by a HCD process, ensuring continuous involvement of users, healthcare professionals, and other relevant stakeholders like researchers or technology developers. In line with participatory research approaches in applied ageing research, users were not only involved as study participants but as active contributors throughout different stages of the development process, including needs identification, concept development, and iterative evaluation. Such approaches emphasize co-creation, mutual learning, and empowerment of end users, which are considered crucial for addressing the heterogeneous needs and preferences for fostering technology acceptance and sustainable implementation [13].

Data from these activities were combined with existing acceptance models such as the Technology Acceptance Model (TAM) [9] or Unified Theory of Acceptance and Use of Technology 2 (UTAUT2) [11] to systematically analyze factors influencing user acceptance and to link empirical findings with established theoretical frameworks.

Health for All: A study in this project illustrates the early-stage involvement of end users within the HCD process. A qualitative research approach was employed to identify barriers to accessing healthcare services, using a semi-structured interview guide that incorporated barriers identified in prior literature (e.g. language barriers, geographical barriers). Empirical data were gathered through

interviews with affected individuals as well as interviews and focus groups with experts in health and social care. The study was carried out across multiple locations, including Graz, Carinthia, and Murska Sobota. In total, 20 affected persons and 12 experts participated. The collected data were analyzed using qualitative content analysis.

REHA2030: Within the REHA2030 project, a teletherapy solution for stroke patients and therapists was developed. A key component addressed the structured assessment of user capabilities as part of the iterative development process. In addition, participatory methods were applied to identify design requirements for tele-therapy solutions, involving users and stakeholders in the early development phases [14]. These activities included workshops and interviews aimed at capturing user needs, expectations, and potential barriers regarding the use of tele-therapy technologies.

Furthermore, a questionnaire ("REHA Assessment") was developed to capture internal and external factors influencing patients' suitability for telerehabilitation, including their ability to use digital technologies. The instrument was applied to 160 stroke survivors in two rehabilitation clinics, and the resulting data were analyzed using statistical methods. Subsequently, the influence of 87 characteristics on suitability was analyzed using both parametric and non-parametric statistical methods [15]. The insights gained from both participatory activities and quantitative assessment informed the refinement of system requirements and supported the alignment of technological solutions with user capabilities. The results contributed to a better understanding of user-related determinants relevant for tailoring digital rehabilitation solutions.

TeleCareHub: Within this project, a platform for informal caregivers of people with dementia was developed. User involvement was realized through iterative evaluation in a real-world context. A pilot study with 56 informal caregivers of people with dementia was conducted. Using a pre–post design, the study evaluated the impact of the intervention on outcomes such as caregiver burden and relationship quality. In addition, factors related to user acceptance were evaluated, providing insights into the feasibility and uptake of the solution and enabling further refinement based on user feedback [16].

SENSHome: This project followed a holistic human-centred design (HCD) approach to develop a smart home and interior design solution for people on the autism spectrum and their caregivers. Requirements were gathered through iterative user involvement, including workshops, questionnaires, and stakeholder discussions with formal and informal caregivers as well as designers and domain experts. These activities enabled the identification of user needs, environmental sensitivities, and contextual requirements, which were continuously translated into design specifications for assistive smart-home functionalities and inclusive furniture elements. The process followed an iterative cycle of understanding users, defining requirements, designing solutions, and evaluating design outcomes in close collaboration with end users [17].

PROTEA: This project applied a human-centered, gender- and diversity-sensitive participatory design approach to the development of 3D-printed lower-leg prostheses with integrated sensor technology. A transdisciplinary team including engineering, orthopedics, movement sciences, psychology, and gender studies collaborated with users and stakeholders in iterative co-creation activities such as interviews, focus groups, and design workshops. These activities supported the development of personas and the derivation of technical and user-centered requirements, which directly informed the iterative design of prosthetic components. The process explicitly integrated an intersectional perspective to address heterogeneous user needs and contribute to reducing gender and diversity gaps in prosthesis design [18].

This experience and theoretical framework have led to comprehensive knowledge about crucial acceptance factors, user needs, and contextual requirements across different target groups resulting in the development of three interlinked components. These components are intended to support digital health literacy and to improve knowledge of digital health tools and assistive technologies.

A Digital Health Lab (DHL): A demonstration and experience space equipped with contemporary assistive and digital health technologies. The DHL enables hands-on exploration of technologies supporting health promotion, independence, safety, and digital health literacy.

A Digital Health Literacy Training Concept: A modular training program derived from empirical insights and established digital health literacy models. Learning objectives and modules were aligned with HCD principles and tailored to different audiences.

An "Ethics as an Opportunity" card set: This card set was developed within an interdisciplinary working group of an innovation platform for intelligent assistance in health, care, and social services. The card set was iteratively designed and evaluated in participatory workshops with stakeholders from healthcare, research, and industry. It serves as a structured reflection tool to address ethical key topics such as autonomy, justice, responsibility, and data protection throughout different stages of technology development and use.

Results

Previous projects have demonstrated that technology affinity, as measured by the Affinity for Technology Interaction (ATI) Scale [19], remains high even in older study populations. Likewise, perceived usefulness and usability of digital health products are generally rated positively. Nevertheless, many digital health technologies fail to be transferred into sustained real-world use.

In the Health for All Project one key finding of the study is a gap in digital health literacy among participants. While many individuals have access to smartphones – representing a potentially valuable resource – they often lack the necessary skills to effectively use these devices and other digital technologies for managing and improving their health. This highlights a disconnect between access to technology and the ability to meaningfully benefit from it in a health context.

In the REHA2030 project, a real-life test of the teletherapy solution was conducted with four patients and seven therapists. The usability of the system was generally high, with slightly better ratings from patients. Patients considered telerehabilitation a useful complement to conventional therapy, despite lower perceived quality compared to face-to-face treatment. Therapists also found the system easy to use but reported challenges in exercise preparation and only moderate integration into daily workflows [20]. Long-term implementation in routine practice has not yet been achieved. Furthermore, the analysis of the REHA Assessment identified technology-related competencies as significant factors influencing suitability for telerehabilitation. In particular, self-reported technological knowledge showed a significant association with suitability ($p = 0.047$; $r = 1.181$). Additionally, the daily use of a smartphone or tablet was also significantly related to suitability ($p = 0.032$; $r = 0.657$). These findings underscore the importance of both perceived digital competence and routine engagement with mobile devices in determining patients' readiness to participate in technology-supported rehabilitation [15].

In the TeleCareHub project, 56 participants with a mean age of 57 years (SD = 12.9) reported a moderate-to-high technology affinity (mean ATI score = 3.5 on a 6-point scale, where 1 indicates low and 6 indicates high affinity). Although participants rated the tested platform as highly useful and usable according to the meCUE questionnaire [21], their intention to use (ITU) was only moderate. Comparable findings have been reported in other projects and studies, suggesting a persistent gap between perceived usefulness and actual or intended technology use.

In the SENSHome project, requirement analysis showed that environmental design factors, sensory sensitivities, and contextual living conditions play a crucial role in shaping technology acceptance, particularly for users with specific cognitive or sensory needs. These findings indicate that acceptance is not only determined by individual competencies but also by the fit between technology and the physical and social environment [17].

Similarly, the PROTEA project demonstrated that gender- and diversity-related factors significantly influence technology design requirements in assistive technologies. The participatory co-design process revealed that heterogeneous user needs must be explicitly considered in order to avoid exclusionary design assumptions and to improve perceived relevance and usability of the technology [18].

These findings support the assumption that additional factors – such as prior experience with technology, habit, hedonic motivation, and social influence, as described in the TAM3 [10] and UTAUT2 [11] models – may contribute to limited technology uptake. To address this gap, a set of interlinked components was developed. These components are designed to bridge the gap between perceived usefulness and real-world adoption by targeting key leverage points identified across the empirical studies, including digital competencies, contextual fit of technologies, and diversity-sensitive design requirements.

The **Digital Health Lab** provides a low-threshold, experiential learning environment that makes digital health and assistive technologies tangible for healthcare professionals, students and the general public. It showcases a broad range of commercially available digital health and assistive technologies, including telemonitoring systems, smart emergency watches, fall detection systems, digital voice assistants, wearable health devices, and serious games for cognitive and motor training. The DHL is not intended as a sales environment but as an educational and demonstration infrastructure.

Integrated into higher education teaching within health-related study programs and accessible to external visitors, the Digital Health Lab is complemented by a structured **Digital Health Literacy Training Concept**. This modular program is based on empirical findings and established digital health literacy models and is tailored to diverse target groups. It integrates foundational perspectives on health and digital health literacy with practical training on smartphones, health apps, wearable devices, smart home components, and other digital tools for health promotion. Additional modules address serious games, social media use, and digital consumption in relation to health. The program further includes national digital health infrastructures such as the electronic health record (ELGA), fostering critical reflection on access, data protection, and responsible use. Together, these activities address not only practical use cases but also critical aspects such as data security, data protection, and ethical implications of digital health technologies (see "Ethics as Opportunity" card set), thereby supporting the development of functional, interactive, and critical digital health competencies and promoting informed, responsible, and sustainable technology use.

The **Ethics as Opportunity card set** enables structured ethical reflection within both the DHL and the training modules. The ethics card set addresses a comprehensive range of key topics relevant to the responsible design, implementation, and use of digital health technologies. Central ethical dimensions include autonomy, privacy, data protection, and transparency in communication, alongside considerations of usability, accessibility, and digital health literacy as prerequisites for informed and self-determined technology use. Further themes such as inclusion, diversity, cultural values and norms, justice, and fairness emphasize the social and societal implications of digital health solutions, particularly with regard to equitable access and participation. In addition, the card set incorporates aspects of safety, non-maleficence, responsibility, efficiency, and long-term impacts. By integrating these topics, the card set supports structured ethical reflection across different stages of development and application, fostering technologies that are not only functional but also socially responsible and sustainable. Each card focuses on a specific ethical theme, provides a concise definition, and offers guiding questions that can be flexibly applied depending on context and development stage. Initial workshop evaluations indicate that the card set supports interdisciplinary reflection and facilitates structured discussion of ethical implications of digital health technologies.

Conclusions and Possible Next Steps

The findings from the presented studies and design projects indicate a persistent gap between positive perceptions of digital health technologies (e.g., perceived usefulness, usability, and technology affinity) and their sustained real-world adoption. While users generally report moderate-to-high acceptance levels, actual or intended use remains limited, suggesting that existing acceptance models such as TAM and UTAUT2 only partially capture the complexity of real-world technology uptake in health-related contexts.

Across the projects, three interrelated categories of influencing factors emerged: (1) individual competencies and digital health literacy, (2) contextual and environmental fit of technologies, and (3) socio-cultural and diversity-related aspects of design and use.

Individual-level factors were particularly evident in the Health for All and REHA2030 projects, where limited digital health literacy and varying levels of technological competence significantly influenced the ability to meaningfully engage with digital health solutions. These findings highlight that access to technology alone is insufficient without corresponding functional and critical digital competencies.

Environmental and contextual factors were prominently addressed in the SENSHome project, which demonstrated that sensory sensitivities, spatial conditions, and everyday living environments significantly shape the suitability and acceptance of assistive technologies. This underscores the importance of aligning technological solutions with users' physical and situational contexts rather than focusing solely on individual capabilities.

Socio-cultural and diversity-related aspects were particularly evident in the PROTEA project, where a gender- and intersectionality-sensitive design approach revealed that heterogeneous user needs must be explicitly considered to avoid exclusionary design assumptions. These findings emphasize that technology acceptance is also shaped by structural and societal dimensions of inclusion, equity, and representation. In addition, the TeleCareHub project confirmed that even when technologies are perceived as useful and usable, this does not necessarily translate into sustained use, reinforcing the existence of a "usage gap" in digital health interventions.

To address these multi-layered barriers, a set of interlinked components was developed, consisting of (i) experiential learning environments (Digital Health Lab), (ii) structured competence development programs (Digital Health Literacy Training Concept), and (iii) structured ethical reflection tools (Ethics as Opportunity card set).

Together, these components extend established acceptance models [9], [11], [12] by embedding individual, environmental, and socio-technical determinants into a practice-oriented intervention framework. This framework provides a basis for addressing the gap between perceived acceptance and actual technology use by targeting key leverage points identified across the empirical studies. Rather than treating acceptance as a purely individual cognitive construct, the presented approach conceptualizes it as an outcome of the interaction between competencies, context, and design-related inclusivity factors.

Future research should focus on systematically evaluating the effectiveness of the proposed components in real-world settings, particularly with regard to their impact on sustained technology use and long-term adoption, as emphasized in existing implementation and evaluation frameworks for digital health interventions [22]. Longitudinal studies are needed to better understand how digital competencies, contextual factors, and socio-cultural influences interact over time and shape technology engagement in everyday life.

Furthermore, participatory and human-centered design approaches should be further strengthened to ensure continuous inclusion of diverse user needs throughout the development and implementation process. This aligns with principles of transdisciplinary research, which emphasize the integration of

multiple stakeholder perspectives and real-world contexts in order to address complex societal challenges [23]. In addition, future work could aim to operationalize the proposed framework by developing measurable indicators for individual, environmental, and socio-technical determinants, thereby enabling more precise evaluation and comparison across different digital health interventions [22].

From a practical perspective, the transferability and scalability of the presented components – particularly the Digital Health Lab, training concepts, and ethics-based reflection tools – should be investigated in different healthcare systems and population groups. This includes examining how such approaches can be integrated into routine care, education, and policy frameworks to support inclusive and sustainable digital health adoption.

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Indoor and Outdoor Navigation for Disabled People: Challenges and Opportunities

Navigating Independence: A Survey of Visually Impaired People's Experiences and Needs

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Abstract

Independent navigation in unfamiliar environments remains a major challenge for blind and visually impaired individuals, despite the availability of assistive technologies. This paper presents the results of a fully accessible online survey investigating navigation experiences, challenges, and technology preferences among people with visual impairments worldwide. The survey was distributed through individuals and organizations supporting visually impaired communities. Our results indicate that smartphone-based applications are the most used digital navigation aids, while a substantial proportion of participants report not using any assistive navigation technology due to cost, accessibility, or usability barriers. Participants reported persistent difficulties in obstacle detection, wayfinding, and navigation in complex environments. Despite a widespread focus on smartphone-based solutions, they expressed a clear preference for wearable and hands-free systems, highlighting a gap between current technology use and user needs. The findings provide a user-centered overview of navigation needs and offer insights into the design and evaluation of future assistive navigation systems.

Introduction

Independent navigation in unfamiliar environments is a fundamental requirement for autonomy, safety, and social participation. For blind and visually impaired (BVI) individuals, navigating everyday spaces such as streets, public buildings, or transportation hubs often involves significant challenges related to orientation, obstacle avoidance, and wayfinding. Although a range of assistive technologies has been developed, their adoption and effectiveness in real-world settings remain limited.

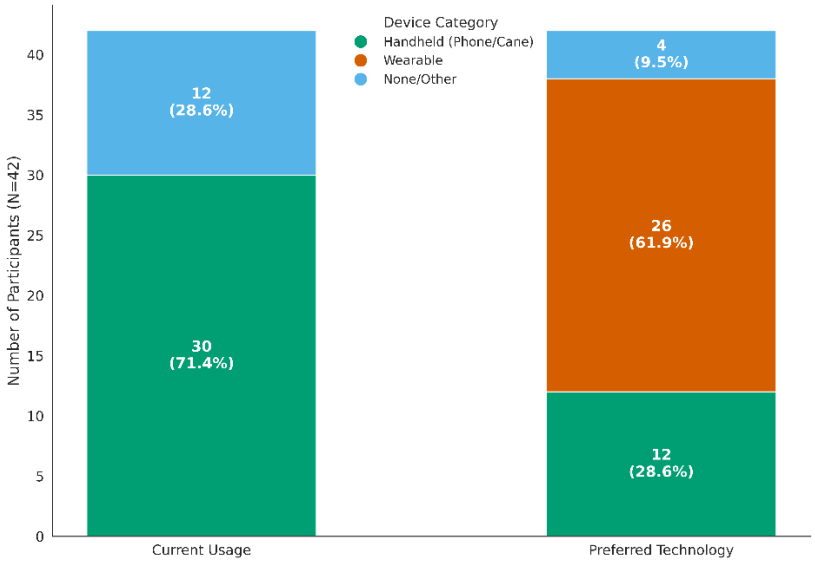


Figure 1: Comparison of current assistive technology use and preferred device categories, illustrating the gap between commonly used solutions and user preferences.

Limited use of assistive technologies should not be interpreted as a lack of need, but rather as a mismatch between user needs and the accessibility, usability, and practicality of available solutions. As

illustrated in Figure 1, while many users rely on handheld solutions such as smartphones in practice, a larger proportion expresses a preference for wearable, hands-free technologies.

What users rely on in practice does not necessarily reflect what they would prefer under ideal conditions. Factors such as cost, ease of use, physical burden, environmental conditions, and regional context strongly influence whether a system is usable in everyday situations. These considerations highlight the importance of grounding assistive navigation research in empirical user experience.

To address this, this paper presents the results of a survey of visually impaired individuals worldwide, capturing navigation experiences, challenges, and preferences related to assistive technologies. The questionnaire included closed- and open-ended questions covering background, technology use, challenges, and navigation needs, and was distributed globally through organizations and individuals supporting visually impaired communities. This work provides a user-centered overview of navigation experiences and needs, complementing existing research that often focuses on technical development. The findings aim to inform and contextualize future research on assistive navigation systems.

The remainder of this paper is organized as follows. First, we review related work, followed by the survey methodology. Afterward, the results of the survey are presented and interpreted, followed by a discussion of limitations, and a conclusion.

Related Work

Research on navigation for blind and visually impaired individuals has explored a wide range of environments and methodological approaches, including outdoor and indoor settings, as well as studies spanning both contexts. Prior work has employed surveys, interviews, and observational studies to investigate navigation challenges, user needs, and interaction strategies.
A substantial body of work has focused on outdoor navigation, particularly in urban and transportation-related settings [1–7]. These studies highlight challenges related to orientation, environmental awareness, and infrastructure accessibility, and emphasize the role of auditory information and spatial understanding in supporting independent mobility.

Indoor navigation has also received considerable attention, especially in unfamiliar or structured environments such as public buildings and campuses. Prior work has identified key challenges related to wayfinding, obstacle awareness, and the availability of relevant environmental information, and has emphasized the importance of user-centered design in defining effective navigation support [8–10]

Several studies have further examined navigation behavior across different contexts and the use of assistive technologies in everyday scenarios, highlighting the influence of situational factors, user preferences, and interaction strategies [11, 12]. In parallel, a large body of work has proposed and evaluated assistive navigation systems, including wearable, vision-based, and multimodal approaches, often in controlled or system-specific settings [13, 14].
Although these studies provide valuable insights, they are often constrained by specific environments, geographic regions, or particular technologies. In contrast, the present work adopts a user-centered perspective through a globally-distributed and accessible questionnaire, aiming to capture navigation experiences, challenges, and preferences reported by visually impaired individuals across diverse real-world contexts.

Survey Methodology

This study investigates the experiences, challenges, and preferences of visually impaired individuals in unfamiliar environments through a fully accessible online questionnaire. Accessibility was a central design requirement, and the questionnaire was tested and refined with input from a visually impaired user, supported by manual evaluation using the Web Accessibility Evaluation Tools (WAVE). A pilot study involving visually impaired and sighted participants was conducted to identify usability issues.

The questionnaire consisted of 17 closed-ended questions (12 single-choice and 5 multiple-selection) and two open-ended questions covering personal background, navigation experiences, and preferences. Conditional branching was applied such that follow-up questions were shown only to participants who reported using digital assistive navigation technologies. Eligibility was based on self-identification as blind or visually impaired, verified through early questions on vision status, onset, and severity. The survey aimed to include participants from diverse demographic and geographic backgrounds. Participation was voluntary and based on implied consent, and no personally identifiable information was collected.

Survey responses were cleaned by removing duplicate and incomplete submissions. All questions were required, resulting in a dataset without missing values. Responses were analyzed using quantitative methods for closed-ended questions and inductive thematic analysis [15] for open-ended responses. Given the exploratory nature of the study and the relatively small sample size, the analysis focuses on descriptive statistics. Inferential or multivariate analyses were not performed, as they would not provide statistically reliable conclusions for the present dataset. For key proportions, 95% confidence intervals were computed using the Wilson score interval [16]. The survey questionnaire and supporting documentation are available in the project repository.

Results

This section presents the results of the survey, including participant demographics, experiences with assistive navigation technologies, and stated preferences.

Participant Background

Participants represented diverse geographic regions and demographic groups, with the largest proportion from Western Europe and North America, followed by Africa and Eastern Europe, as shown in Table 1. The sample included a broad age distribution and a balanced representation of acquired and congenital visual impairment, with most participants reporting severe impairment or total blindness.

Table 1: Demographics and visual impairment characteristics of 42 participants. Values are reported as number of participants n (%).

Region	Africa	11 (26.2%)
	Asia Pacific	4 (9.5)
	Eastern Europe	9 (21.4)
	Latin America & Caribbean	1 (2.4)
	Western Europe & North America	17 (40.5%)
Age Group	Under 15	0 (0,00%)
	15-30	9 (21.4)
	30-45	14 (33.3%)
	45-60	14 (33.3%)
	Above 60	5 (11.9%)
Gender	Male	25 (59.5%)
	Female	16 (38.1%)
	Non-binary	1 (2,4%)
Severity	Mild	4 (9,5%)
	Moderate	6 (14.3%)
	Severe	17 (40.5%)
	Total blindness	15 (35.7%)
Onset	Acquired	24 (57.1%)
	Congenital	18 (42,9%)

Experience with Assistive Navigation Technologies

To understand how these demographic characteristics, relate to real-world navigation behavior, we next examine participants' use of assistive technologies. Table 2 presents these results across five

categories: technology type, usage settings, overall satisfaction, feedback adequacy and responsiveness (time to react). Smartphone-based applications were the most reported assistive technologies, although a substantial proportion of participants reported not using any digital navigation tools. Nonuse of digital assistive navigation technologies varied across levels of visual impairment. Participants with total blindness and moderate impairment showed higher rates of nonuse (approximately one third), whereas no nonuse was observed among participants with mild impairment. This suggests that individuals with more severe vision loss face greater barriers to adopting existing technologies. Among users, usage was primarily oriented toward outdoor or mixed environments. Satisfaction levels varied, and many participants reported insufficient feedback, particularly in environments with dense obstacles. Perceived responsiveness was also inconsistent, with many users indicating limited time to react to obstacles, highlighting potential safety concerns.

Table 2: Experiences with digital assistive navigation of the 32 technology users; reported as n (%), and 95% confidence interval (CI).

Technology	Smart Cane	2 (4.8%)	[1.3, 15.8]
	Smartphone apps	28 (66.7%)	[51.6, 79.0]
	Smartwatch apps	0 (0.0%)	[0.0, 8.4]
	Other technologies	2 (4.8%)	[1.3, 15.8]
	None	10 (3.8%)	[13.5, 38.5]
Setting	Indoor only	2 (6.3%)	[1.7, 20.1]
	Outdoor only	16 (50.0%)	[33.6, 66.4]
	Both, in- & outdoor	14 (43.8%)	[28.2, 60.7]
Satisfaction	Very satisfied	3 (9.4%)	[3.2, 24.2]
	Satisfied	15 (46.9%)	[30.9, 63.6]
	Neutral	4 (12.5%)	[5.0, 28.1]
	Unsatisfied	5 (15.6%)	[6.9, 31.8]
	Very unsatisfied	3 (9.4%)	[3.2, 24.2]
	Uncertain	2 (6.3%)	[1.7, 20.1]
Adequacy	Sufficient for navigation	6 (18.8%)	[8.9, 35.3]
	Insufficient indoors	4 (12.5%)	[5.0, 28.1]
	Insufficient outdoor	8 (25.0%)	[13.3, 42.1]
	Inufficient with obstacles	10 (31.3%)	[18.0, 48.6]
	Insufficient in noise	3 (9.9%)	[3.3, 24.2]
	Other limitations	1 (3.1%)	[0.6, 15.7]
Responsiveness	Always sufficient	2 (6.3%)	[1.7, 20.1]
	Usually sufficient	11 (34.4%)	[20.1, 52.6]
	Sometimes sufficient	12 (37.5%)	[22.9, 54.7]
	Rarely sufficient	4 (12.5%)	[5.0, 28.1]
	Never sufficient	2 (6.3%)	[1.7, 20.1]
	Uncertain	1 (3.1%)	[0.6, 15.7]

Despite the use of these technologies, participants reported frequent challenges related to route finding, landmark identification, and obstacle detection. Head-level obstacles were reported most often, followed by hazards at chest, ground, and leg levels, reflecting the multi-level nature of real-world navigation risks, as presented in Table 3.

Preferences and Expectations

In response to these challenges, clear patterns emerged regarding user expectations for assistive technologies. These were examined across three dimensions: device form, feedback modality, and desired system characteristics. Table 4 summarizes the relationship between severity of visual impairment, technology nonuse, and device preferences, with percentages calculated within each severity group. Across all levels of visual impairment, wearable devices were consistently favored, particularly among

individuals with severe impairment or total blindness. While handheld solutions were also selected, they were more commonly chosen by participants with severe impairment or total blindness, although they remained less preferred overall. A similar trend was observed across age groups, with wearable devices favored in all categories. As illustrated in Figure 1, a clear discrepancy exists between current usage and preferred device categories: although handheld solutions, particularly smartphones, are most commonly used in practice, a larger proportion of participants expressed a preference for wearable, hands-free technologies.

Table 3: Navigation challenges and collision risk by obstacle height; reported as n (%), 95% CI; multiple selections allowed.

Challenges	Finding indoor landmarks	22 (52.9%)	[37.7, 66.6]
	Finding outdoor landmarks	24 (57.1%)	[42.2, 70.9]
	Detecting obstacles ahead	19 (45.2%)	[31.7, 59.5]
	Route finding	29 (69.1%)	[54.0, 80.9]
	Other challenges	6 (14.3%)	[6.7, 27.6]
Obstacle Height	Head level	32 (76.%)	[61.5, 86.5]
	Chest level	17 (40.5%)	[27.0, 55.5]
	Leg level	16 (38.1%)	[25.0, 53.2]
	Ground-level	17 (40.5%)	[27.0, 55.5]
	None	1 (2.4%)	[0.4, 12.3]

Table 4: Technology nonuse and device preference by impairment severity: reported as n (%).

Severity	Nonuse	Wearable	Handheld	Other
Mild	0 (0.0%)	3 (75%)	1 (25%)	0 (0.0%)
Moderate	2 (33.3%)	5 (83.3%)	0 (0.0%)	1 (16.7%)
Severe	3 (17.6%)	10 (58.8%)	6 (35.35)	1 (5.9%)
Total blindness	5 (33.3%)	8 (53.3%)	5 (33.3%)	(13.3%)

Beyond device form, participants expressed preferences regarding how navigation information should be delivered. Audio and multimodal feedback were the preferred options, whereas tactile-only and simple auditory cues were selected less often, as shown in Table 5. Among tactile options, feedback delivered to the hands and arms was preferred most frequently.

Table 5: Device and feedback preferences; reported as n (%), and 95% CI; multiple selections allowed for tactile feedback location.

Form	Wearable	24 (57.1%)	[46.8, 75.0]
	Handheld	16 (38.1%)	[17.2, 43.6]
	Other	12 (28.6%)	[27.0, 55.5]
Feedback	Audio	6 (14.3%)	[27.0, 55.5]
	Multimodal	5 (11.9%)	[19.1, 46.0]
	Tactile	4 (9.5%)	[10.0, 33.3]
	Beep	1 (2.4%)	[3.8, 22.1]
Tactile Location	Hands and arms	24 (57.1%)	[42.2, 70.9]
	Wrists	16 (38.1%)	[25.0, 53.2]
	Shoulders	12 (28.6%)	[17.2, 43.6]
	Forehead	6 (14.3%)	[6.7, 27.8]
	Feet	5 (11.9%)	[5.2, 25.0]
	Waist	4 (9.5%)	[3.8, 22.1]
	Legs	1 (2.4%)	[0.4, 12.3]

Table 6: Route preferences and desired assistive navigation features; reported as n (%), 95% CI; multiple selections allowed

Route Factors	Shortest route	16 (38.1%)	[25.0, 53.2]
	Fastest travel time	15 (35.7%)	[23.0, 50.8]
	Lowest-cost path	11 (26.2%)	[15.3, 41.1]
	Obstacle-free paths	26 (61.9%)	[46.8, 75.0]
	Route information	23 (54.8%)	[39.9, 68.8]
	Continuous guidance	20 (47.6%)	[33.4, 62.3]
	Rapid rerouting	16 (38.1%)	[25.0, 53.2]
Key Features	Low mental load	22 (52.4%)	[37.7, 66.6]
	Low physical effort	20 (47.6%)	[33.4, 62.3]
	Ease of use	34 (81.0%)	[66.7, 90.0]
	Obstacle avoidance	20 (47.6%)	[33.4, 62.3]
	Low device weight	22 (52.4%)	[37.7, 66.6]
	Low cost	27 (64.3%)	[49.2, 77.0]
	Remote assistance	10 (23.8%)	[13.5, 38.5]

Participants' expectations were also reflected in the route characteristics and system features they prioritized. Table 6 presents these route preferences and desired assistive navigation features. Obstacle-free paths and access to route information were selected most often, followed by continuous guidance. In addition, participants emphasized ease of use, low cost, reduced cognitive and physical effort, and effective obstacle avoidance. To facilitate comparison of the relative importance of system features, Figure 2 provides a ranked visualization of the responses summarized in Table 6.

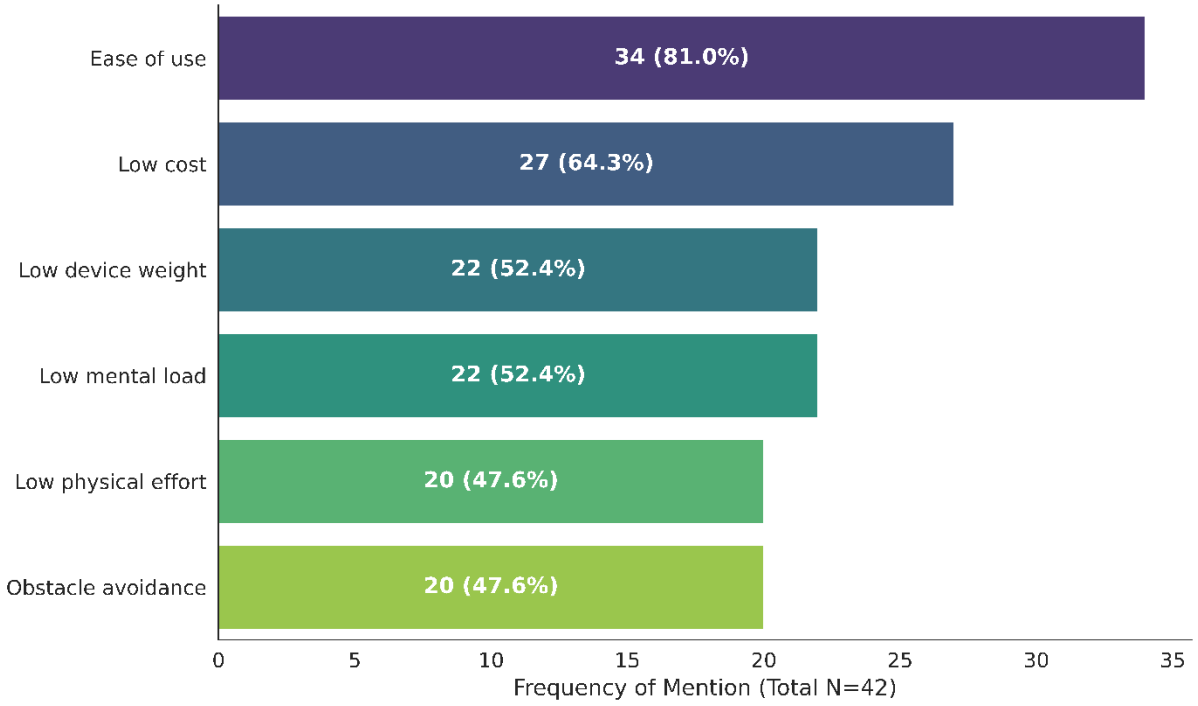


Figure 2: Importance of assistive navigation system features based on participant responses.

Insights from Open-Ended Responses

To complement the quantitative findings, open-ended responses provide additional insights into user experiences and expectations. These responses emphasized simplicity, low-effort interaction, and integration with familiar, everyday devices. Participants preferred unobtrusive and discreet solutions that complement existing mobility aids, such as canes, rather than replacing them. Reliable and actionable guidance, including obstacle-related information and clear route instructions, was frequently requested.

Practical considerations, particularly affordability, accessibility across regions, and operational constraints such as offline functionality, were also highlighted.

Discussion

The findings of this study highlight persistent challenges faced by visually impaired individuals in wayfinding, spatial awareness, and obstacle avoidance. These challenges likely arise because real-world environments contain complex and multi-level obstacles that are not fully captured by current assistive technologies or traditional mobility aids. As a result, assistive navigation systems must improve their ability to detect and communicate spatial information across different obstacle levels, particularly beyond ground-level hazards. The results indicate that outdoor environments remain especially challenging, contradicting current research attention on indoor navigation. This can be explained by the higher variability and unpredictability of outdoor environments, as well as the lack of standardized infrastructure, where conditions such as noise, crowd density, and layout change continuously. Therefore, assistive navigation systems should prioritize robustness and adaptability to real-world conditions rather than relying on assumptions derived from structured or controlled environments.

A clear gap is observed between the availability of assistive navigation technologies and their actual use, with many participants reporting that they do not rely on digital tools. This pattern reflects practical barriers reported by participants, including limited access, high cost, and the difficulty of obtaining suitable technologies. It also highlights environmental constraints that may vary across countries, as well as reliance on alternative navigation strategies. These challenges are particularly relevant for users with higher levels of impairment. In addition, reports of insufficient feedback and limited responsiveness suggest that current systems may not deliver timely and actionable information in safety-critical situations.

A further discrepancy emerges between current technology use and user preferences. While most participants rely on smartphone-based navigation in practice, this appears to reflect availability rather than optimal usability. In contrast, a majority expressed a preference for wearable, hands-free solutions, indicating a shift toward interaction modalities that have the potential to reduce physical and cognitive burden. Together with the strong emphasis on ease of use and low cost, these findings indicate that nonuse is driven primarily by practical barriers rather than a lack of demand.

These findings further suggest that assistive navigation systems should support multiple device form factors rather than relying on a single solution. While wearable devices enable hands-free interaction, handheld solutions may still offer advantages in terms of control and familiarity, particularly for users with different levels of impairment and navigation strategies. Similarly, the diversity of preferred feedback modalities, including speech, multimodal, and tactile cues, reflects variability in environmental conditions and individual preferences. This indicates that no single feedback mechanism is universally effective, and that future systems should incorporate adaptable and multimodal interaction strategies that respond to both user needs and situational constraints.

Finally, participants prioritized obstacle-free routes, ease of use, and low cognitive effort over traditional efficiency metrics such as shortest path or travel time. This shift reflects the safety-critical nature of navigation for visually impaired users, where reliability and mental workload are more important than efficiency. As a result, evaluation frameworks for assistive navigation systems should move beyond purely technical metrics and incorporate user-centered criteria such as safety, cognitive load, and real-world usability.

Limitations

This study has several limitations that should be considered when interpreting the results. First, the survey relied on online recruitment, which may introduce sampling bias toward individuals with internet access and familiarity with digital tools. As a result, individuals with limited access or those who

rely on alternative communication methods such as Braille may be underrepresented. The survey was conducted exclusively in English, which excluded non-English speakers and limited representation across regions. Furthermore, the data collection period was constrained by time limitations, which may have influenced the overall sample size and distribution. Future studies addressing these limitations could contribute to a more comprehensive understanding of navigation challenges and needs among visually impaired individuals.

Conclusion

This paper presents the results of a fully accessible online survey examining navigation experiences, challenges, and preferences among visually impaired individuals. The findings provide a user-centered view of everyday navigation needs and highlight the diversity of experiences across users and contexts. They further reveal a gap between current technology use and user preferences, with participants often relying on available handheld solutions while expressing a clear preference for wearable, hands-free systems. Participants emphasized ease of use, affordability, obstacle avoidance, and access to route information, indicating that assistive navigation is evaluated not only in terms of technical performance but also in terms of safety, cognitive effort, and practical usability. Therefore, future systems should support flexible device form factors and interaction modalities, prioritize safety and cognitive simplicity, and provide low-effort, adaptive, and multimodal feedback. Affordability and practical accessibility should be treated as central design requirements, while evaluation should extend beyond technical metrics to include usability, reliability, and real-world effectiveness. Despite limitations related to sampling and scope, this study contributes structured evidence that can inform future assistive navigation research and development.

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A Depth-Based Mobility Aid Development Platform for Users with Blindness and Low Vision

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Abstract

Most people with blindness or low vision experience a much reduced ability for independent mobility. While far-field mobility and orientation have seen great advances through GPS applications and recently possibly also AI scene descriptors; the near-field counterpart is still dependent on white canes and guide dogs alone. This work presents a technological platform to provide the means for realistic user tests in built environments of a depth-based auditory feedback device to aid in near-field mobility. The platform consists of a wearable sensor unit featuring a depth camera, wired to a computer unit worn in e.g. a bag or backpack, and a pair of headphones. It allows for adequate depth acquisition, offline, in real-time, with a wide field-of-view, and in varying ambient conditions. In addition, it is relatively compact and lightweight for a research device. Thus, it should serve quite sufficiently as the new technological basis for upcoming user tests, evaluating functionality and ergonomics of the proposed mobility aid Audomni as well as the continued development of it.

Introduction

Blindness and low vision (BLV) has an immense impact on quality of life and independence. It increases the prevalence of anxiety, depression, falls, fractures and premature death [1]. Decreased independent mobility plays a major role in this [2], and the primary mobility aids of today, the white cane and guide dog, do not mitigate it sufficiently for most people with BLV. While a great number of technological aids have been proposed to replace or complement canes and dogs in near-field mobility, still none has seen meaningful adoption. However, as the problem with BLV mobility persists, it is imperative to keep trying. By leveraging advancements in technology, accumulated learnings from previous proposals of the field, as well as the fields of ergonomics and human-computer interaction, this work presents a new mobility aid development and evaluation platform. The aim of it is to allow for portable and realistic testing in relevant built environments, through both internal testing and user tests including participants with BLV; as well as allow for rapid prototyping of depth-based audio feedback algorithms.

State of the Art

There is a considerable and ever-increasing amount of electronic mobility assistive device (EMAD) proposals for BLV mobility, e.g. [3–5]. They vary widely in scope and aim. For instance, a significant sub-field pertains EMADs for indoor navigation only. Also, some EMADs are meant as complementary to existing aids, and some as replacements. Some address near-field obstacle detection and avoidance, and others far-field orientation. Device types include mobile applications, wearable, handheld, cane-like, walker-like, and robotic (today often dog-like). The most popular EMAD type, which enjoys abundant acceptance, is likely GPS applications with voice feedback. With the rise of convolutional neural nets and generative AI, scene descriptor-type EMAD proposals have become popular as well.

While GPS and possibly AI apps address far-field BLV mobility needs to various degrees, when it comes to the near-level there is still virtually no EMAD in use, either by itself or in conjunction with a cane or dog. There are many possible reasons, for instance barriers of uptake like cost, as well as limited availability and training opportunities. These have however been alleviated when it comes to canes and dogs, suggesting deeper issues with EMAD proposals. It is possible that simply no EMAD has struck an adequate balance between functionality, ergonomics, and hedonistic qualities (e.g. aesthetics and

feedback pleasantness); but regardless, a major issue is likely that no EMAD has been shown to actually increase independent mobility. Further, while indoor navigation in especially unknown areas is an important issue to tackle, outdoor navigation in both known and unknown areas is of least the same importance.

This project sets aim at providing a technological platform that facilitates evaluating and developing an EMAD that can first and foremost help with outdoor BLV near-field mobility in known and unknown areas, by itself or alongside another mobility aid, e.g. cane or dog.

Methodology

The design requirements for the proposed platform stem from previous work in the Audomni research project. The Audomni concept is an EMAD which aims to translate visual information into non-verbal auditory feedback such that users can traverse built environments without sight. In the project, Audomni was first tested with a physical prototype with two participants with BLV [6]. The concept was then iterated on based on those tests, and with support of a proposed design model incorporating published best practices for EMAD development, guidelines from BLV advocacy groups, and conventions of user-centered design and ergonomics [7]. The updated version was then tested in virtual reality with a heterogeneous distribution of 19 participants with BLV, with promising result [8].



Figure 1: The proposed blind and low-vision mobility aid development platform. To the left is the sensor unit, housing the depth camera and inertial measurement unit, attached to a bracket-style neck-mount with chest support. At the back stands the computer unit with battery attached. In the middle are the bone-conductive headphones. The computer unit can be worn with a shoulder strap, or by placing it in a bag or backpack.

Next, the main aim of the current platform is to become the technological foundation of a new iteration of Audomni, with the goal of enabling real-life tests mirroring those of the previous in virtual reality.

The audio feedback from the planned EMAD requires adequate depth accuracy, field-of-view (FoV), angular resolution, and in various outdoor conditions, e.g. – and typically challenging for depth camera used – direct sunshine. Depth frames should be available with minimum latency and all data processing made onboard. Further, the size, weight, and overall physical design should be comfortable, light, and convenient; ideally enough so that users could envision it as an end-product. Additionally, the battery

life must support testing sessions of reasonable length. It is also desirable that development and evaluation workflow with the platform is practical.

The proposed platform consists of three units: sensor, computer, and feedback, cf. **Chyba! Nenalezen zdroj odkazů.**. The sensor unit features a wide-angled, continuous-wave indirect time-of-flight (CWToF) depth camera; an absolute-orientation inertial measurement unit (IMU); and a custom interface printed circuit board (PCB). The unit has a 3D-printed plastic housing with a slot to attach it to a tripod or an arc-shaped neck-bracket.

The computer unit comprise an embedded computer, an USB WiFi-adapter, another custom interface PCB, an external removable battery, as well as a sound card PCB. Besides the battery, everything is enclosed in a 3D-printed plastic housing. The unit also features a 3D-printed interface for the power tool battery to slot into. The battery connects to the interface card which then powers the computer and sensor units. Those are connected through a wrapped 20-lead ribbon cable.

Lastly, the feedback unit consists of a pair of off-the-shelf Bluetooth headphones. These include an "ambient" mode which allows for hearing ambient sounds like traffic beside the sound feedback. The hardware of the respective units are listed in **Chyba! Nenalezen zdroj odkazů.**.

Table 1: List of primary off-the-shelf hardware included in the platform.

Depth camera	EVK75027-110-940-1 (partial), Melexis
Embedded computer	Jetson Nano Developer Kit, Nvidia
Inertial measurement unit	BNO055 Absolute Orientation Sensor, Adafruit
Headphones	Zen Hybrid Pro Classic, Creative
Audio transmitter	BT-L3, Creative
Battery	Professional ProCORE18V 4.0Ah, Bosch
USB WiFi adapter	Archer T3U, TP-Link

Results

Acceptable depth acquisition is possible at a variety of ambient conditions with the proposed platform. It has been trialed in temperatures ranging -10°–20° C; with materials of different reflectivity including asphalt, gravel, wood, snow, and line marking paint; and crucially, in different lighting conditions, e.g. indoor lighting, as well as outdoor at night, dusk, cloudy, and in full, unobstructed daylight, including with the sun in the camera FoV. The last condition is of note due to the CWToF technology, which uses active illumination it has to filter out from ambient light. This is typically difficult in daylight, with the considerable illumination produced from the sun. Regardless of conditions, the camera must provide dependable readings from all objects closer than a certain distance, for any subsequent user feedback to afford safe navigation. This distance surely depends on many factors, including user-dependent ones as well as feedback type. For the current platform, 2.0 m is considered adequate, as that corresponds to a point on the ground 1 m away for a camera height of 1.75 m (i.e. a camera at shoulder-height at the male 95th percentile). In the worst trialed scenario: sun in the FoV at 11° altitude, and measuring ground-level wet asphalt; the camera still provided reliable readings up-to 2.3–2.5 m. A quite promising result. Conditions that have not been trialed yet include warmer ambient temperatures; as well as rain, snow and fog. However, the 3D-printed housings – which also affords proper thermal management of the camera – likely do not provide adequate protection for the electronics for such wet conditions at this time.

Depth acquisition properties are listed in Table 2, and an example scene is featured in **Chyba! Nenalezen zdroj odkazů.**. Assuming a normally distributed distance error, there is a 95 % likelihood of an error >= 3 STD every ~1100 pixels, and there are 4800 pixels per frame. For the platform, an error of 3 STDs corresponds to 28 mm at 2.0 m distance. The angular resolution corresponds to a Euclidean resolution of 2.6 %, or 52 mm at 2.0 m distance. It is not straightforward to say if this distance error and/or angular resolution can enable safe BLV mobility. Whereas a singular protrusion of e.g. 10 mm

at ground level certainly can be enough to trip on, it is both uncertain how common such situations are, and if they do not pose a similar risk in sighted mobility. It is possible that adequate properties can only be identified empirically. What can be said, is that if the STD or angular resolution is too large for safe BLV mobility in general, it should not be of orders of magnitude. It is also possible to trade angular and possibly time resolution for better STD, and STD for angular resolution. Various camera settings could also be revisited in efforts to improve these aspects. In any case, the current performance should still afford meaningful user tests in built environments.

Table 2: Depth acquisition properties.

Pixel resolution	80x60
Field-of-view	109°x87°
Angular resolution	~1.5°
Frame rate	58 FPS
Mean absolute percentage error	1.5%
STD	0.46%
Orientation reading asynchrony	<10 ms

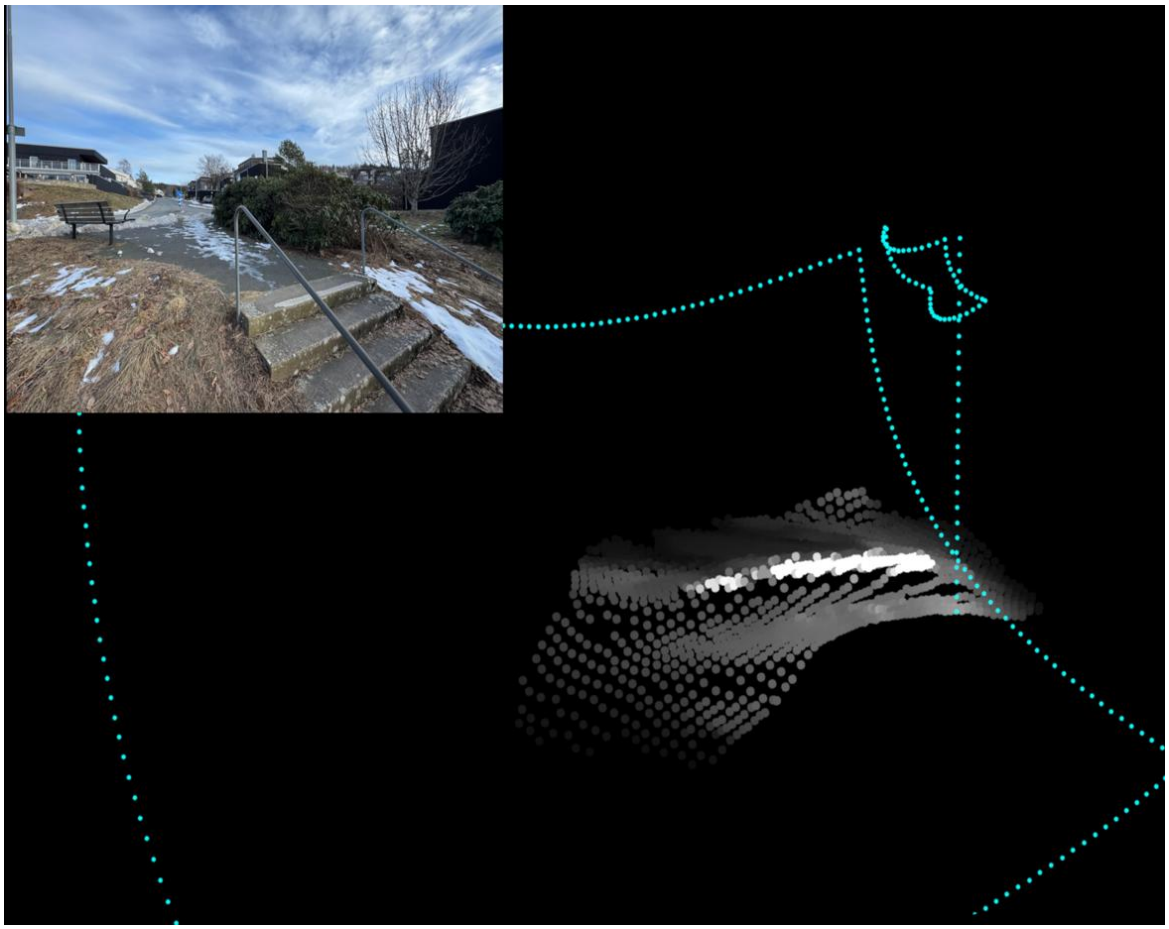


Figure 2: Depth acquisition example in point cloud format and scene photograph (depth camera and platform not included). The straight light-blue line represents the vertical axis of the camera at the point of capture, from its center to estimated ground level; the curved light-blue frames represent the camera field-of-view at 250 and 3000 mm away; and the white-to-gray dots represent pixels with valid depth readings, the dot brightness corresponds to the amplitude of the depth reading. In this scene, the camera is situated ~1800 mm directly above the second-to-last of a flight of steps. The last step and the following level pathway can be seen in front of the camera perspective. To the right in the camera perspective (in the background of the figure) the readings just reach the path-

adjacent bush, resulting in a group of slightly raised points. To the left in the camera perspective (in the foreground), a slight unevenness in the points can just be made out from the patch of inclined and grassy ground.

The power tool battery allows for ~2 h of operation. This should be quite sufficient for user tests, especially since it is replaceable in the same manner as for power tools. The type of battery was chosen for this reason, for the off-the-shelf charging station, its power delivery capabilities, and its ruggedness.

Depth acquisition example in point cloud format and scene photograph (depth camera and platform not included). The straight light-blue line represents the vertical axis of the camera at the point of capture, from its center to estimated ground level; the curved light-blue frames represent the camera field-of-view at 250 and 3000 mm away; and the white-to-gray dots represent pixels with valid depth readings, the dot brightness corresponds to the amplitude of the depth reading. In this scene, the camera is situated ~1800 mm directly above the second-to-last of a flight of steps. The last step and the following level pathway can be seen in front of the camera perspective. To the right in the camera perspective (in the background of the figure) the readings just reach the path-adjacent bush, resulting in a group of slightly raised points. To the left in the camera perspective (in the foreground), a slight unevenness in the points can just be made out from the patch of inclined and grassy ground.

The sensor unit weights 0.13 kg. To make it wearable, an arc-shaped bracket to be worn around the neck and with support from the chest has been produced. The form was based on earlier brackets to be worn on the head, which in turn were based on anthropometric data of head length, breadth, and shapes. However, it was eventually deemed preferable to lower the camera to increase its relative performance. This also had the added benefit of making it easier and more comfortable to wear, and arguably a bit more inconspicuous. A downside is that the camera no longer follows users' head movements, but only their body, which could have an impact on externalizing the sound feedback. The biggest drawback is however that the camera no longer can detect head-height obstacles. For future versions this should be addressed, possibly with additional sensors. Six people with various head sizes have internally trialed the brackets with the camera attached. All stated no discomfort, and that it should be adequate for a test session of about 45 min.

The computer unit feature fittings for a shoulder strap, though it also fits in mid-sized purses, sling bags or backpacks, which should be more comfortable and discreet. The choice of bag could be up to the user. The unit weighs 1.10 kg including battery, which should be manageable by most users for a test session, especially in a backpack or with a shoulder strap across the body.

Efforts have been made to keep the units as small, lightweight, unobtrusive, and discreet as possible within given resources and time. However, while they are relatively so for a development platform, they are quite bulky and conspicuous in an absolute sense. It remains to be seen to what degree the overall physical design is acceptable to potential end-users; though the aim is primarily a somewhat representative baseline from which to start evaluating this important aspect. For this, the physical design is deemed suitable.

Bone-conductive headphones have been used earlier in the Audomni project since they intrinsically allow for ambient sounds, but today "ambient modes" is commonplace in headphones. To use such headphones instead was chosen since the audio from bone-conductive headphones can be difficult to distinguish in loud or windy scenarios, and as they can be difficult to use with caps in cold weather. Wired headphones were also originally chosen to minimize latency. However, recent Bluetooth versions have seen much improvement in that aspect, making wireless headphones more feasible. The particular model of headphone for the platform was chosen as it supported the Bluetooth Low Energy Audio standard, which allows for reduced latency versus earlier standards; as well as for accepting audio broadcasts to multiple recipients. The latter point is a considerable benefit in testing scenarios, as then the test leader can listen in to the feedback the tester receives.

A multitude of popular software libraries and programming languages are made available through the Linux operating system of the embedded computer. This in turn affords flexibility and rapid prototyping

of various feedback algorithms; as well as of fundamental functionalities, e.g. hardware drivers, status sounds, sensor setup, and automatic application initialization when the battery is connected. Advantages also include extensibility, for instance through the USB WiFi-adapter, which simplifies software development and file sharing over secure shell protocol.

Besides providing absolute orientation readings at 100 Hz, the IMU also allow for some rudimentary user interaction through its accelerometer. Tap detection software has been implemented to recognize up-to quadruple taps on the right and left side of the sensor unit. This can be used to set various camera settings, as well as launch and deactivate camera capture. While it is workable in a development setting, a limited amount of time was spent on this feature, which in combination with the—for tap detection—limited sensor rate, makes it unideal for participant use in testing.

A number of external and internal software capabilities have been developed for the platform. External software enables playback of the custom file format for the camera and IMU data; calibrating the intrinsic camera matrix; as well as performing polynomial regression on the camera data for depth calibration. Internal software provides capabilities for bringing up the camera and IMU at boot or otherwise, a barebones, audio-only, menu system, the tap detector, and for visualizing and recording the camera and IMU data.

The most fundamental drawback of the platform is its focus on depth-based auditory feedback. First, there are many other sensors that could be of use, e.g. ultrasound, radar, or regular cameras. Second, many if not most EMAD proposals utilize haptic feedback. Offering that would substantially increase the possible design space of user feedback, and then maybe also the chances of reaching a successful near-field EMAD. However, while audio displays are fairly standardized, haptic displays are decidedly not so. Choices relating to positions, type, and number of tactile actuators determine what type of feedback is possible, likely making a generic solution unattainable.

Conclusion

All in all, the presented technological platform provides sufficient capabilities for the next prototype of the depth-based, near-field EMAD Audomni to be used in real built environments, and in a variety of conditions. Further, for a research prototype it can be regarded as relatively lightweight and slim. This should minimize the impact the physical design could have on the perceived functionality. It can also allow for users to imagine it as if it were a commercialized device. Through this, the platform shows appreciable potential for meaningful learning outcomes from upcoming user tests in real built environments, both objective regarding functionality, as well as subjective regarding functionality and physical design.

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Digital Accessibility – From Inclusive Design and UX to Implementation and Evaluation

Making Accessibility Work in Practice: European ICT Accessibility Standards under the European Accessibility Act (EAA)

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Abstract

The European Accessibility Act (EAA) establishes binding accessibility requirements for a wide range of ICT products and services across the European Union. Its practical impact depends on the coherence and usability of the harmonized technical standards used to demonstrate compliance. This contribution discusses the interdependencies between the ICT accessibility standards that are developed in support of the EAA and how they can be seen as a translation layer between inclusive design principles and real-world implementation. It also indicates some of the standards' limitations, inviting the HCI community to engage in standardisation efforts to increase relevance of standards, supporting accessibility at scale.

Introduction

Accessibility has long been recognized as a fundamental requirement for inclusive participation in digital society. Within the Human-Computer Interaction (HCI) community, decades of research have produced a rich body of knowledge on inclusive design, assistive technologies, and user-centred approaches that address the needs of people with disabilities. These efforts have significantly improved awareness and practice at the level of individual systems and design processes.

However, the conditions under which accessibility is realized are changing. Increasingly, accessibility is not determined solely by designers or organizations but is shaped by broader regulatory and infrastructural frameworks. Legal requirements, procurement rules, and technical standards now define what accessibility means in practice, what is measured, and what is delivered to users. This reflects a broader understanding of technology as shaped not only by design decisions but also by regulatory and socio-technical forces, where "code" and technical artefacts can act as forms of regulation in themselves (Lessig [1]; Winner [2]).

In the European Union, the European Accessibility Act (EAA) [3] represents a major step toward harmonizing accessibility requirements across member states. By introducing legally binding obligations for a wide range of ICT products and services, the EAA aims to improve accessibility at scale. Yet the directive itself does not specify how accessibility should be achieved in practice. Instead, a set of harmonized European standards are developed based on the standardization request [4] issued in connection with the EAA implementation to translate high-level requirements into concrete technical specifications.

This shift raises important questions. How are abstract accessibility principles expressed as legal obligations and next transformed into testable requirements? How do multiple standards interact to define accessibility in practice? And to what extent do these standards reflect the lived experiences of users with disabilities?

Previous research has shown that compliance with formal accessibility requirements does not necessarily guarantee usable or accessible experiences in practice, particularly for blind users and other groups relying on assistive technologies (Power et al. [5]; Petrie and Kheir [6]).

This paper argues for greater involvement in standardization processes so that standards become meaningful tools bridging regulatory frameworks and practical implementation. It conceptualizes the

accessibility standards as a translation layer within the socio-technical system of accessibility. It analyses the structure and interdependencies of ICT accessibility standards developed under the EAA, focusing on the standards developed by ETSI. It examines how the standards operationalize accessibility through detailed technical requirements.

The paper promotes accessibility standardisation not merely as a technical or administrative activity, but as a form of design at scale, with profound implications for users, developers, and society. It concludes by highlighting the need for stronger engagement of the HCI and accessibility research communities in shaping these standards.

Accessibility Standards as a Translation Layer

In many design and development contexts, accessibility standards are perceived as external constraints – checklists that must be satisfied to achieve compliance. This perception is reinforced by guideline-based evaluation approaches, which have been shown to capture only part of the accessibility experience and may fail to reflect real user interaction challenges (Power et al. [5]; Henry et al. [7]).

Such a perspective undermines the potential role that standards should play in shaping accessibility outcomes. This paper encourages another, arguably more productive, perspective. It frames accessibility standards as a translation layer between high-level inclusive design principles (such as those articulated in Clarkson et al. [8]), accessibility legislation and concrete products and services that respond adequately to the real accessibility experience (see Picture 1).

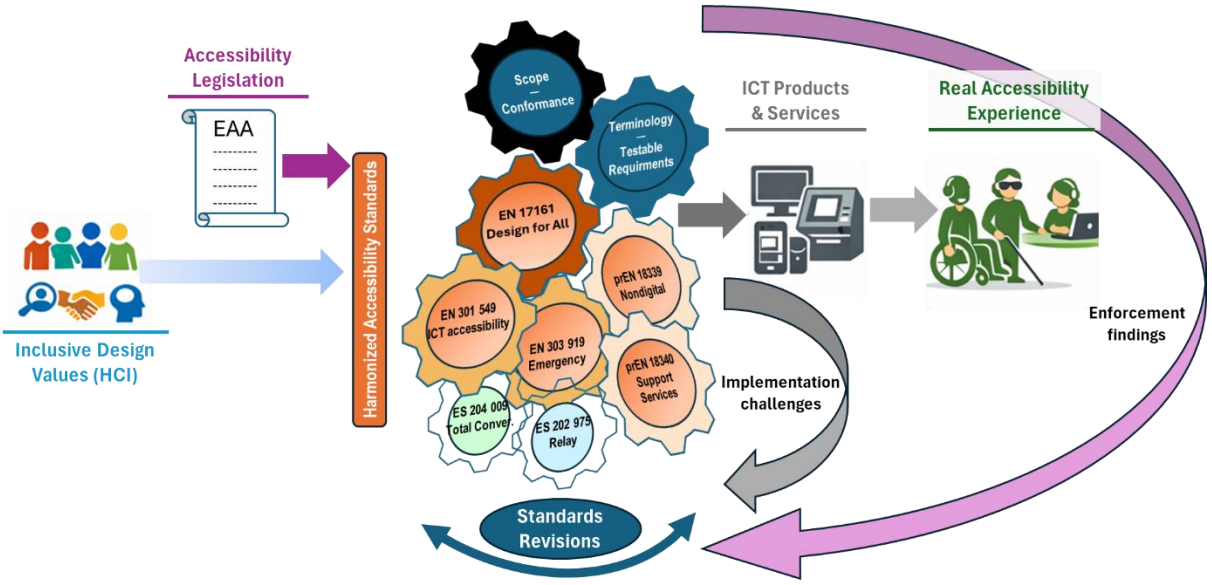


Figure 1: Accessibility standards function as a translation layer (depicted as a gearbox) between inclusive design values, accessibility legislation and the real-word ICT systems and users.

At one end of the standards layer are concepts such as usability, accessibility, and user diversity – concepts that are inherently complex, context-dependent, and often difficult to quantify, along with the requirements defined in the accessibility legislation. At the other end are technical systems that must be designed, implemented, and tested within constraints of time, cost and technological feasibility, and the ultimate end-users that verify in reality delivered accessibility.

Standards mediate between these domains by translating abstract concepts into structured, testable requirements. This notion of translation aligns with broader socio-technical theories describing how abstract concepts are transformed into operational artefacts within institutional contexts (Star and Griesemer [16]). The translation process necessarily simplifies, formalizes, and operationalizes aspects of accessibility. The quality of the final translation is critical and the process involves design decisions:

what aspects of accessibility are prioritized, how they are defined, and how they are measured. In this sense, standards can be understood as design artefacts in their own right, embedding particular values and assumptions about users and use contexts (Winner [2]).

Furthermore, in the context of an area such as the ICT accessibility requirements covered by the EAA, where multiple standards are developed to address various facets of ICT accessibility, their mutual complementarity is essential. When standards are coherent and well-aligned with user needs, they can support consistent and scalable accessibility. When they are fragmented or incomplete, they can introduce ambiguity, create barriers to implementation, and ultimately fail to deliver meaningful accessibility.

Understanding standards as a translation layer between the legislation and inclusive design principles on one side and the real products and services on the other highlights their central role in shaping the accessibility, underscoring their importance and impact on the ultimate ICT. It also emphasizes the importance of continuous interaction between the different layers. The subsequent revisions of standards are typically triggered by further development of legislative frameworks (introduction of new mandatory requirements), by implementation challenges or by enforcement findings. At both stages, issues may concern issues with precision or clarity of the requirements, test clauses, or gaps in the standards.

The European Accessibility Act and Standardization Landscape

The EAA [3] establishes accessibility requirements covering ICT products and services such as websites, mobile applications, e-books, self-service terminals. The directive specifies a generic set of functional performance criteria that any ICT should meet. In addition, it extends the accessibility requirement beyond the ICT product and service, requiring for accessibility provision of certain information about the use and accessibility of ICT ensuring it is presented in accessible formats of any type: digital, non-digital, and also including customer support services.

To facilitate implementation and the assessment of conformity with the EAA, the European Commission issued a standardization request [4] mandating European standardization organizations – ETSI, CEN and CENELEC – to develop and revise harmonized accessibility standards. These standards provide the technical specifications that enable manufacturers and service providers to demonstrate conformity with the EAA. The resulting landscape is inherently modular and distributed, comprising multiple standards that address different aspects of accessibility. Key standards include:

- Revision of ETSI/CEN/CENELEC EN 301 549 [9], addressing accessibility requirements for ICT products and services.
- New ETSI EN 303 919 [10] standard for the accessibility and interoperability of emergency communications and for the answering of emergency communications by the public safety answering point (PSAPs) (including to the single European Emergency number 112)
- Revision of CEN/CENLEC EN 17161:2019 Design for All - Accessibility following a De-sign for All approach in products, goods and services - Extending the range of users [11]
- New CEN/CENELEC prEN 18340 standard setting up requirements on the accessibility of non-digital information related to products.
- New CEN/CENELEC prEN 18339 standard for the accessibility of support services related to products and services.

This modular approach reflects the complexity of the regulated domains and leverages specialized expertise. However, it also creates challenges. Standards are developed by different organizations, under different methodological traditions, and at different stages of maturity. This can lead to variations in terminology, scope, and level of precision.

A particularly important distinction concerns the principle of testability. Standards developed by ETSI emphasize precise, testable requirements, ensuring that compliance can be objectively verified. In

contrast, standards developed by CEN/CENELEC often adopt broader, more qualitative formulations. While these may better capture complex aspects of accessibility, they can also introduce ambiguity.

Poorly aligned standards can introduce ambiguity for designers and developers, create uncertainty for evaluators, and ultimately reduce accessibility for users. This challenge is consistent with findings from usability and accessibility research showing that ambiguities in requirements and evaluation criteria can lead to inconsistent implementation and interpretation (Brajnik [12]; Lazar et al. [13]). Coherent and well-aligned standards can support consistent interpretation, lower implementation barriers, and enable accessibility to be addressed systematically rather than ad hoc.

The M/587 mandate [4] requires standards for five areas of ICT accessibility to support the EAA [3]: general accessibility requirements for all ICT products and services, including digital formats and electronic communication, emergency communications – accessibility requirements for emergency calls, including PSAPs and the European Emergency number 112, information – specifying what information must accompany accessible ICT products and services, accessibility of non-digital format – requirements for presenting information in non-digital formats and accessibility of support services – ensuring accessibility of customer support. Table 1 links the EN standards to these five areas and includes two additional standards for electronic communication accessibility guidance. The EN 301 549 [8] plays a central role by covering general accessibility requirements, while other standards complement it in specific domains such as emergency communication or support services.

Table 1: The EAA areas of requirements and the relevant ICT accessibility standards. x – identifies the standard with the mandatory require-ments to meet the EAA requirements, o – identifies the standard that concerns not the features of the ICT, but the process

	General	Emergency communications	Information	Non-digital format	Support services
EN 301 549 [8]	x		x[6]		
EN 303 919 [10]		x	x[7]		
prEN 18 339				x	
prEN 18 340					x
EN 17 161 [11]	o	o	o	o	o
ES 204 009 [14]	v	v			
ES 202 975 [15]	v	v			

The mapping presented in Table 1 reveals a potential gap within the current standardization landscape, particularly with respect to requirements governing the provision of accessibility-related information. This gap appears to result from an imprecise definition of scope across existing standards and may be addressed in future revisions or through emerging standards that are presently under development. This observation underscores the complexity inherent in formulating a cohesive suite of standards that collectively support legislation encompassing a wide range of accessibility requirements. The gap is not examined in detail in this contribution. Instead, the following section describes how the legislative requirements are translated into the testable standard clauses primarily in the context of the ETSI ENs.

[6] The standard requires only a subset of information required by the EAA.
[7] Included requirements are limited to information about accessible emergency communications aspects.

Mapping of the Accessibility Legislation Requirements into Harmonized Standards

From Functional Requirements to Testable Technical Clauses

The EAA [3] as the legislative act defines a set of requirements for ICT products and services that ought to be met by an ICT to be accessible. These accessibility requirements are supposed to guarantee that generic functional performance criteria contained in Annex I Section VII of the directive are met.

The purpose of the harmonized standards is to translate these legislative requirements into a set of requirements that are specific, precise and testable so that the conformance of the products and services with the EAA requirements can be proved.

ETSI EN 301 549 is the main standards with generic accessibility requirements for ICT products and services, where clauses 5 through 13 provide the normative set of requirements, translating the EAA's requirements into specific technical requirements that a given ICT product or service needs to meet to be accessible.

ETSI EN 303 919 has a similar structure. In addition to clauses containing specific technical requirements that need to be met to claim accessibility of emergency communications delivered by a given ICT product or service, this standard defines also a set of functional requirements that need to be met to ensure accessibility of the emergency communications (clause 6). An analogous set of functional performance criteria is also included in EN 301 549, based on the EAA Annex I Section VII.

To show conformance, i.e. verify accessibility, each of the normative requirements defined in the ENs is accompanied by a corresponding test clause. Only when all applicable tests are passed, the conformance with the EAA requirements can be claimed.

The Level of Precision of Harmonized Standards (ENs) in Addressing the EAA Essential Requirements

As discussed above, the main intention of the EN 301 549 and other harmonized standards is to translate the generic essential legal requirements of the EAA into a set of testable and specific technical requirements.

To illustrate the complexity of this seemingly simple task, the EAA requirements for electronic communication services to provide real-time text in addition to voice communication. The requirement that in the text of the EAA directive is contained in the expression: "*provid[e] real time text in addition to voice communication*", see the EAA Annex I Section IV point (a)i.

The EN 301 549 translates this 9-word requirement into a set of technical requirements specified in clause 6.1, 6.2, 6.3 and 6.4, and 13.1 if the service is expected to support emergency communication, totalling in 21 specific clauses and their corresponding test clauses. Additionally, clause 6.0 applies requiring that each of the tests specified for clauses 6.1-6.4 requirements needs to be passed under all relevant scenarios specified in clause 6.0 (for example, when communicating with a client from the same but also from another service provider). Depending on whether the communication service is supposed to provide emergency communications, 4 to 8 scenarios are applicable, yielding in total 84 to 168 specific tests that need to be passed to show that the electronic communication system is accessible with respect to providing real-time text in addition to voice communication.

The reason for the apparent multitude of the technical requirements and tests needed to address one generic essential functional requirement of the EAA is that the technical requirements specified as standard clauses need to be precise and unambiguously testable. They should also be limited to essential accessibility aspects, not mandating aspects that could be beneficial otherwise, for example for usability reasons.

Multi-Document and Hierarchical Structure of Harmonized Standards

While the EN 301 549 provides a self-contained set of requirements, the EN 303 919 exemplifies a case where the harmonized standard requires in a normative way following other standards. The EN 303 919 contains a number of normative references providing additional specification of the requirements that need to be followed in order to meet the EN 303 919 requirements. It is important to recognize this hierarchical and multi-document structure in order to claim conformance with the EN 303 919, and hence the EAA requirements for accessible electronic communications. The multi-document structure in the context of the EN 303 919 has been introduced in order to minimize the size of the EN 303 919 but also to tackle the practical challenge to deliver a robust harmonized standard for technologically complex area. Given that the emergency communications is likely to change and evolve over time, it is nearly impossible to provide a definite set of requirements. Therefore, the core of the EN 303 919 contains a set of functional requirements that shall always be fulfilled to ensure accessibility. How this is achieved, depending on the communication technology is further specified by reference to other standards.

The EN 301 549 incorporates this approach only in a nonnormative manner, pointing out to other standards for guidance on how to meet the given requirements. The other standards are then provided as informative references and called out explicitly in the context of relevant mandatory requirements.

This approach of referencing other standards in normative or informative ways keeps the main standard robust and current, while allowing updates to requirements to happen more quickly through separate, simpler revision processes for the referenced standards.

Limitations in Addressing Essential Requirements

Given the ultimate prescription to maintain a high level of precision in translating the EAA essential requirements into testable technical specifications in the two ETSI standards on ICT accessibility – EN 301 549 and EN 303 919, the standards have two limitations in addressing the EAA accessibility requirements:

First, not all requirements can be addressed fully at the prescribed level of precision at present. Among the requirements that are challenging are for example the requirement of sufficient audio quality (provision of enhanced audio features and audio clarity, see the EAA Annex I Section I point 2(g) [1], and high fidelity audio, see the EAA Annex I section I point 2(o)(iii) [1]), or ease of information understanding (the EAA Annex I Section I point 1(a)ii and (b)ii, Section II point b(ii), Section III point b(ii) [1]).

Audio quality at the moment is addressed by the requirement of providing audio within a specific frequency range (see EN 301 549 v4.1.1 clause 6.1.2 [3]). The sufficient frequency range is indispensable to achieving good audio quality. However, it does not directly define the level of delivered quality. Robust methods for testing speech and multimedia transmission quality exist. However, not all of them are suitable in the context of the general ICT accessibility standards due to their relative complexity and resource intensity. The HCI field has recognized a challenge in accessibility evaluation, where measurable technical proxies are often used in place of more complex experiential qualities that are harder to formalize and standardize (Brajnik [12]). Moreover, and critically – while test methods exist there are no established metrics defining sufficient for accessibility levels of audio quality aspects. Such levels need to be verified and established in the course of careful investigations.

With regard to cognitive ease of information understanding, both accepted and reliable test methods as well as metrics are missing. The difficulty of capturing experiential dimensions has been widely documented in accessibility research, particularly in relation to cognitive accessibility and usability beyond compliance (Petrie and Kheir [6]; Power et al. [5]). Further work is needed to develop means for expressing the experiential or perceptual aspects of ICT accessibility so they also can be expressed in

the form of precise, objective, and reproducible technical requirements and included in harmonized standards such as EN 301 549 or EN 303 919.

Notably, both audio quality and cognitive ease of information understanding are being considered to be included at the level of normative requirements in the standards authored by CEN/CENELEC concerning the accessibility of non-digital formats of information and support services. This highlights the difference in the approaches within the different standardisation bodies, and introduces inconsistencies in the standardisation processes.

Second, the harmonized standards per the standardisation request mandate [2] are prohibited from definition of applicable assessment methods. This is a serious problem, because the overall accessibility assessment is inherently related not only to the aspects that are assed but also to the way in which the evaluations are conducted. In most, if not all, ICT accessibility cases, complete and full testing of all aspects of ICT would require extreme resources. Therefore, a sound methodology, involving robust sampling approaches, needs to be deployed in order to assess the level of accessibility of the given ICT. As the ENs provide only a set of individual testable requirements, depending on the deployed assessment approach, the ultimate accessibility evaluation may differ substantially. The lack of standardized guidance on assessment procedures poses a significant risk in reliability of the conformance claims. This issue echoes longstanding concerns in accessibility evaluation regarding the variability of methods and the resulting inconsistencies in reported accessibility levels across different evaluators and contexts (Henry et al. [7]; Lazar et al. [13]). Future efforts are needed to consider how to address this deficiency.

Conclusion and Future Directions: Implications for HCI Practice and Research

The European Accessibility Act [3] represents a major opportunity to advance accessibility at scale. Realizing this potential depends not only on legal requirements, but on the quality and coherence of the technical standards that give them practical meaning. By framing accessibility standardization as a translation layer between inclusive design principles and real-world systems, this work positions standardization as a legitimate and necessary concern for the HCI community.

The contribution outlines the emerging landscape of the critical ICT accessibility standards and invites HCI researchers and practitioners to engage more actively with accessibility standardization and regulatory processes. ICT accessibility standards are becoming powerful tools for shaping the ultimate inclusive technologies beyond individual interfaces and applications. From a socio-technical perspective, these standards can be understood as regulatory artefacts that actively shape technological systems and user experiences, rather than merely describing them (Lessig [1]).

Decisions made within standards committees, and even earlier at legislative stages, have real, broad and lasting implications for design practice. Yet these decisions often occur outside traditional HCI venues and without the benefit of empirical insights from user-centred research. This disconnect limits the extent to which standards can reflect the lived experiences of people with disabilities. Bridging this gap requires integrating empirical user-centred research into standardization processes, addressing a challenge long identified in HCI between formal compliance and actual usability in practice (Power et al. [5]; Petrie and Kheir [6]).

The analysis highlights a fundamental dilemma with the harmonized standards framework: while it is highly effective in operationalizing functional requirements that can be precisely specified and verified, it is far less suited to capturing experiential or perceptual dimensions of accessibility. Therefore HCI expertise – particularly in user-centred design, usability, and accessibility evaluation – can play a critical role in shaping standards that are both rigorous and meaningful.

Prior work in accessibility evaluation has highlighted the inherent tension between testability and real-world usability, where formally verifiable requirements do not always correspond to meaningful accessibility outcomes for users (Petrie and Kheir [6]; Power et al. [5]). The contribution invites reflection

on how HCI researchers can more effectively contribute to regulatory and standardization contexts, easing the tension and bridging the gap between empirical research, design practice, and policy implementation. It describes some of the existing limitations with regard to robustness of the testing frameworks included in the standards (i.e. their methodological weakness due to the lack of standardised assessment methods) gives examples of specific areas that at the moment it is debatable if they can be adequately addressed by the standards due to insufficient research establishing robust test methods or levels of performance. Involvement offers an opportunity to embed inclusive design principles into the infrastructures that govern technology development, consequently increasing the accessibility. Ultimately, improving ICT accessibility at scale requires treating standardization not as a peripheral activity, but as a core site of design, where technical, regulatory, and human factors intersect.

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A Proposed Accessible Cyber Security Support (AcCeSS) Framework

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Abstract

To enhance accessible cyber security, the AcCeSS provides a practical framework for evaluating accessibility in cyber security. Our main contribution lies in articulating such an approach. The farmwork bridges the gap between theoretical perspectives, technical and design considerations, ultimately contributing to a more comprehensive and effective practical framework. The pattern introduces a user-centred framework for identifying and categorising cyber security solutions. This model provides accessibility dimensions, criteria-based scoring, impact ratings, and fixed recommendations across a wide range of security features and disability types. It aims to address potential issues and to develop user-friendly systems that promote equitable and inclusive access. The groups of accessibility experts were asked to review and validate the AcCeSS. This feedback provided a positive indication of the suitability of the proposed framework, while also identifying specific areas for refinement. The final version incorporates this feedback. The AcCeSS framework can help stakeholders, including developers, designers, and policymakers, create secure systems that are accessible, safer and better aligned with user expectations. Further study is suggested to apply the framework to stakeholders and evaluate its effectiveness in real-world scenarios.

Introduction

The software industry is constantly evolving certain aspects, such as the accessibility of software products and services, which require ongoing attention due to their close relationship with user experience. However, accessibility, in general, remains a low priority in many technologies' development processes [1]. This lack of priority is also evident in cyber security-related development, leading to accessibility barriers for users with disabilities [2].

Although accessibility standards and guidelines exist [3], and accessibility topics are increasingly included in Computer Science [4, 5], much of the literature shows accessibility issues are commonplace for disabled users. Additionally, many professionals are not adequately prepared to engage with accessibility in practice and there are inadequate accessibility tools and resources [6, 7]. These results highlight the inaccessibility of software and services. In security and privacy contexts, such a gap becomes especially significant. By looking at current cyber security design guidance, it tends to prioritise technical aspects while overlooking usability; achieving a balance requires intentional effort from designers and developers to ensure usable and inclusive security systems [8]. In line with Furnell, Helkala [9], a framework is needed to bridge the gap between user rights and authentication methods. An "inclusive approach to cyber security" is required to increase the safe use of digital technologies for individuals with varying disabilities [2].

This study aims to raise awareness of the importance of creating accessible solutions that ensure equal access for all users. The lack of progress in developing an accessible security framework has resulted in a significant accessibility gap. These problems contribute to the accessibility of people with disabilities. To address this gap, our main research question is: How to design and develop accessible cyber security safeguards that overcome critical barriers affecting disabled users? In this study we propose a practical framework to help improve the accessibility of cyber security. Building on the principle that security and privacy should be embedded into digital technologies from the earliest stages of the design process [10], this framework is designed to support a wide range of stakeholders with diverse roles

and technological backgrounds, including designers, developers, deployers and standards advisors. It provides a structured approach that facilitates informed decision-making across the technology lifecycle, ensuring that security, privacy, and accessibility considerations are systematically addressed.

We begin by describing and contextualising the proposed framework. Then, we outline the validation methods prepared for evaluation by accessibility experts. The results of this validation are presented next. In conclusion, we summarise the key findings and contributions of this work. Finally, the acknowledgements section recognises those who supported this research.

Framework Overview

The **A**ccessible **C**yber **S**ecurity **S**upport (AcCeSS) framework provides the conceptual model for understanding accessibility in cyber security. The AcCeSS framework is designed to guide stakeholders in identifying and addressing accessibility barriers that may arise when users with disabilities interact with cyber security safeguards. The framework integrates user characteristics, security features, accessibility dimensions, associated assessment criteria, and predefined recommendations into a structured decision-making process that supports inclusive and accessible cyber security design and facilitates practical implementation across diverse user groups.

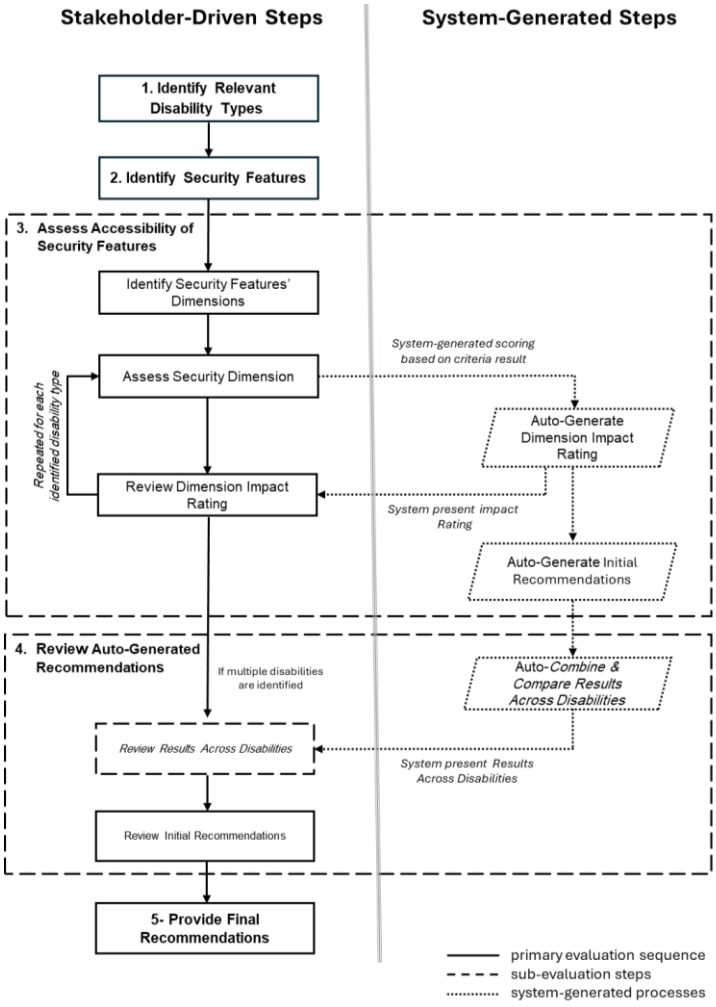


Figure 1: AcCeSS framework workflow

Figure 1 illustrates the main workflow of the framework. The left side indicates tasks that require stakeholder involvement, decision-making, or manual input, while the right-hand side represents system-driven processes such as criteria scoring, and the generation of recommendations. The framework

process starts by identifying the intended user groups and the security features to be evaluated, followed by assessing nine relevant accessibility dimensions using predefined criteria. The dimensions are:

1. **Cognitive Complexity (CC)** refers to the level of mental effort required to understand, remember and respond to information in security interactions, such as setting passwords, reading cookie banners, or answering security questions. High complexity can create barriers for users with cognitive or learning difficulties, memory issues, or anyone facing unclear instructions.
2. **Reading Demand (RD) or Information load** refers to the amount of written content a user should read and understand to complete a security-related task. This can include lengthy cookie consent banners, privacy notices, or warning messages. High reading demand can create barriers for users with dyslexia, cognitive impairments, limited literacy, or those using screen readers
3. **Time Sensitivity (TS)** refers to security features that require quick user responses within a fixed time limit such as one-time passwords (OTPs) or session timeouts. Short time windows can create barriers for users who need more time due to slower input, or assistive technology use. This situation can result in repeated failures or lockouts.
4. **Dexterity Demand (DD)** refers to the level of physical precision or coordination required to complete a security action, such as clicking small buttons or icons, or solving drag-and-drop CAPTCHAs. High dexterity demand can pose challenges for users with motor impairments, tremors, or limited control of their limbs.
5. **Input Demand (ID)** refers to the amount and type of manual input a user must provide to complete a security task. This includes actions such as entering passwords, typing one-time passwords (OTPs), or verifying identity through various clicks, typing, or gestures. High input demand can be challenging for users with upper-limb impairments, fatigue, or limited device control, and potentially increases the risk of input errors.
6. **Multi-device Interaction (MI)** involves security processes that require users to switch between multiple devices such as receiving an OTP on a phone while logging in on a computer or verifying identity through a mobile app. These cross-device steps can create barriers for users with motor, visual, or cognitive impairments, who may struggle with coordination, device handling, or remembering multi-step instructions.
7. **Modality Constraints (MC)** refer to security features that rely on a single sensory channel such as visual or auditory input which can limit access for some users. For instance, a CAPTCHA that relies only on visual input can exclude individuals who are blind, while an audio-only verification may be inaccessible for those who have hearing impairments.
8. **Visual Demand (VD)** refers to the level of visual attention, and detail recognition required for a security task. It considers whether the task relies only on visual input and output or involves additional cognitive load. Examples of high visual demand tasks include reading small or low-contrast text, identifying distorted images in CAPTCHAs, or locating visual cues such as color-coded buttons or icons. High visual demand can pose challenges for users with low vision, colour blindness, or those who are blind.
9. **Error Tolerance (ET)** refers to a system's ability to support and recover from user mistakes during low- to medium-risk interactions. These interactions might include actions like mistyping search keywords, entering non-critical data, or navigating through form fields. The emphasis is on how easily users can correct or undo simple errors without facing penalties or disruptions. High error tolerance in these scenarios helps users maintain their orientation and confidence. While low error tolerance can create significant barriers for users, especially those with cognitive, motor, or visual impairments, leading to frustration and exclusion.

Each dimension should be assessed individually, using specific criteria groups, to identify accessibility barriers related to the user group and security feature. The criteria consist of six categories: baseline

criteria; consistency & predictability; error recovery & feedback; operational & load growth; adaptability & compatibility with assistive technologies (AT); and flexibility & alternatives. Together, these groups support a systematic assessment across different accessibility dimensions. Each category represents a specific aspect of human interaction and expected behaviour regarding security features, which may either facilitate effective task performance or pose accessibility challenges (see Appendix). Table presents an example of the assessment criteria table, used to evaluate the Time Sensitivity (TS). Stakeholders should review all six assessment criteria for each dimension and mark each applicable criterion (✓). A total score is calculated based on the number of criteria marked (ranging from 0 to 6), with higher scores indicating a greater impact on accessible cyber security.

Table 1: An example of the assessment criteria for Time Sensitivity dimension

Accessibility Dimension of Cyber Security	Criteria Group/ Sub-Dimension	Assessment Criteria (☑ indicates the criterion is applicable)	
Time Sensitivity (TS)	Baseline Criteria	1. Task has time limits.	✓
	Consistency & Predictability	2. Users must react and respond quickly (e.g., within seconds).	✓
	Error Recovery & Feedback	3. The time limit disrupts task flow.	✓
	Operational & Load Growth	4. Task demands constant attention and rapid action, giving users little time to think and act (e.g., detecting small visual changes or entering characters like J/j/i quickly).	✓
	Adaptability & Compatibility with AT	5. Task completion is difficult using assistive technologies (e.g., screen readers, switch devices).	✓
	Flexibility & Alternatives	6. Users cannot adjust, pause, or extend the time limit.	✓
		Total Score	6

The outcome of this evaluation includes an accessibility impact rating and a set of initial recommendations that are automatically generated, based on the triggered criteria. The initial recommendations for each dimension offer concrete, actionable design guidance that enhances usability, reduces accessibility barriers, and ensures that security features are both protective and inclusive of diverse user needs. The initial recommendations are relevant to the high- and moderate-level rating criteria for the disability identified by stakeholders. Table 2 presents an example of a recommendations table for Time sensitivity dimensions that have a high impact. This enables stakeholders to quickly recognise high-impact accessibility barriers and identify appropriate design solutions, assess accessibility interactions related to security features, and provide final recommendations.

After reviewing the initial recommendations table, stakeholders should provide specific recommendations tailored to their roles and responsibilities. It should be noted that not all recommendations related to each dimension represent a compulsory application to reduce accessibility barriers. Some actions may have a limited impact or may be less feasible to implement due to technical, security, or organisational constraints. However, when multiple dimensions show difficulty at the same time, such as Time Sensitivity combined with input demand, their combined effect can create a significant accessibility barrier. Similarly, if one of the dimensions appears as a low accessibility barrier, while others are not. Therefore, the initial recommendations should be interpreted collectively, not as a checklist where every item must be applied. Stakeholders should prioritise the recommendation actions linked to high-impact dimensions and then consider medium-impact recommendations based on feasibility, security requirements, and the overall user experience. For instance, in each dimension at least one recommendation could improve the accessibility of cyber security.

Table 2: An example of initial recommendations for evaluating the time sensitivity dimension.

Accessibility Dimension of Cyber Security	Impact Rating	Total Score	Criteria Code	Initial Recommendation
Time Sensitivity (TS)	High	6	TS1	Ensure time constraints are meaningful and considerate of different user abilities and interaction contexts. Show a clear countdown timer and early warnings before timeout. Avoid hidden expiry times.
			TS2	Implement grace periods and enable asynchronous completion (e.g., "verify within minutes"). Provide consistent countdown or progress indicators and include options for "Resend code" or "Repeat action".
			TS3	Enable session persistence and autosave. Provide "resume task" options to prevent losing progress. Give early warnings using clear, plain-language alerts before timeout.
			TS4	Avoid complete restarts after minor delays. Use easily readable codes (e.g., avoid visually similar characters). Provide customization options. Avoid simultaneous tasks that require quick reactions along with cognitive load, such as number-based codes, and ensure readability and customization options.
			TS5	Ensure full compatibility with assistive technologies. Provide multiple input methods (keyboard, mouse, voice). Offer alternative verification channels (SMS, email, authenticator app, phone call) and allow repeated attempts without penalty.
			TS6	Provide a "pause" or "extend timer" option where appropriate. Support persistent verification options and user-controlled timing settings.

As a final step, stakeholders should prioritize recommendations and outline a structured implementation plan. The final recommendation structure should be organized according to the level of accessibility impact identified. This hierarchy ensures that stakeholders focus on addressing the most significant and wide-reaching barriers first, while also acknowledging improvements that benefit particular disability groups. The final recommendation framework follows a three-level prioritisation:

1. **Priority Fixes** for dimensions with high impact across multiple dimensions in a single disability assessment, or high impact across multiple disability groups.
2. **Targeted Improvements/ Group-Specific Enhancements** for dimensions with high or medium impact for one disability group or a subset of users.
3. **Secondary Improvements** for dimensions with medium impact across dimensions or across disability groups.

This prioritisation approach ensures that the accessibility barriers with the broadest and highest impact are addressed first, while still capturing important improvements for individual user needs.

Framework Validation Methodology

This study adopts accessibility and cyber security experts assessing the appropriateness, clarity, and conceptual soundness of the developed framework. The purpose of employing expert validation in this study is to evaluate the proposed AcCeSS framework, which addresses a novel approach to enhancing

the accessibility of cyber security for individuals with disabilities. Since no existing interaction framework specifically addresses this issue, the AcCeSS framework represents a contribution and therefore requires comprehensive validation. Expert validation is essential to ensure that the framework and its content are conceptually clear and appropriate for their intended purpose. In addition, this process helps identify potential issues at an early stage, allowing refinements to be made prior to implementation.

The accessibility and cyber security experts were asked to review and validate the proposed framework. They were asked to evaluate the relevance, clarity, and completeness of the proposed framework. This study selects a group of experts who can provide informed and relevant feedback on the validation materials. The selection process focused on individuals with significant experience and knowledge in areas such as UX design, digital design, software development, and cyber security. This ensures that their insights will meaningfully contribute to the validation process. A total of 3 experts participated in this study. This group was invited to participate in the validation process, and the materials were shared with them via email. Each expert was provided with two documents: (1) a set of instructions outlining the required evaluation aspect and the type of feedback expected, and (2) The AcCeSS framework file containing comprehensive documentation of the framework. The materials were distributed to the experts, and responses were collected over a period from 1 March to 13 April.

Accessibility Expert Findings

Expert review involves collecting opinions, suggestions, and feedback to assess the quality and suitability of the developed materials. The experts were asked to evaluate whether the instructions, descriptions, explanations, and examples were clear, consistent, and meaningful. They were also invited to identify any missing elements and provide additional recommendations for improvement. The feedback was given as comments and annotations in the shared documents. These comments were thoroughly reviewed and analysed, leading to improvements in the coherence, consistency, and practical application of the framework. The experts were chosen based on their professional experience, academic background, and familiarity with the research subject area. They represent a range of expertise, including cyber security, human-centred perspectives, and accessibility. This diversity allowed for a thorough evaluation of the proposed framework from multiple perspectives. The varied backgrounds of the experts enabled a comprehensive assessment of the materials from multiple viewpoints. This approach involved each expert independently evaluating the proposed framework, ultimately strengthening the validation process.

After agreeing to participate in the study, the experts received the validation materials. Their overall responses were positive, indicating a general consensus on the clarity and relevance of the materials provided. The expert validation process provided valuable insights into the proposed AcCeSS framework. They noted that the materials were generally well-structured and clearly presented. However, they suggested a number of minor revisions and additions to further improvement clarity, completeness of the framework. The feedback indicated that while the underlying concepts were appropriate, some terminology needed further clarification to avoid potential ambiguity. No major structural changes were required, indicating that the framework was well-developed. Overall, the involvement of multiple accessibility experts contributed to a comprehensive evaluation from diverse perspectives, supporting the validation. Feedback from the experts indicates that they thoroughly engaged with the material and provided relevant observations as a result.

Conclusion

This work provides a practical approach for applying the AcCeSS framework for supporting the evaluation of accessibility in cyber security towards more inclusive and informed accessibility practice. Our main contribution lies in the articulation of such a framework approach, building on some of our previous work. Our approach bridges the gap between theoretical perspectives, technical and design

considerations, ultimately contributing to a more comprehensive and effective practical framework. Further study is needed to apply the framework to stakeholders and evaluate its effectiveness in real-world scenarios.

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Appendix: Dimension Assessment Criteria

Dimension	Assessment Criteria (☑ indicates the criterion is applicable)	
Cognitive Complexity (CC)	Task requires the user to make at least one decision to continue.	□
	Task requires memorizing multiple elements (e.g., username + password).	□
	Interface uses inconsistent elements or layout.	□
	Content contains technical Jorgen or unclear instructions.	□
	Process includes many sequential steps or multiple decision that increase mental load.	□
	Task requires recalling information that is not visible (e.g., hidden actions, key options buried in text or menus).	□
	Total Score	0
Reading Demand (RD)	Text or interface elements are lengthy, dense, or difficult to scan.	□
	Poor text contrast or lack of clear layout hierarchy increases reading effort.	□
	Written information demands high comprehension and attention, which increases cognitive load using legal, formal, or technical terminology.	□
	Task requires motor effort (e.g., scrolling) at the same time as reading or interpreting critical information.	□

Dimension	Assessment Criteria (☑ indicates the criterion is applicable)	
	Task is difficult or impossible to complete using assistive technologies (e.g., screen readers)	□
	Heavy content forces immediate decisions without options to continue, delay, or revisit later.	□
	Total Score	0
Time Sensitivity (TS)	Task has time limits.	□
	Users must react and respond quickly (e.g., within seconds).	□
	The time limit disrupts task flow.	□
	Task demands constant attention and rapid action, giving users little time to think and act (e.g., detecting small visual changes or entering characters like J/j/i quickly).	□
	Task completion is difficult using assistive technologies (e.g., screen readers, switch devices).	□
	Users cannot adjust, pause, or extend the time limit.	□
	Total Score	0
Dexterity Demand (DD)	Task requires precise motor control to accurately select or manipulate interface elements (e.g., selecting small buttons, tapping tiny icons, performing precise gestures).	□
	Task requires continuous or sustained physical actions (e.g., long-press, dragging, holding buttons), increasing physical effort.	□
	The task requires simultaneous motor precision and timing during interaction, increasing cognitive and motor coordination demand.	□
	Task offers little or no tolerance for accidental slips, tremors, or unintended movements.	□
	Task is difficult or impossible to complete using assistive technologies or without fine motor control (e.g., no keyboard alternative).	□
	Users cannot choose alternative input methods or adjust interaction mode (e.g., no option for larger touch targets or voice input).	□
	Total Score	0
Input Demand (ID)	Task requires multiple or rapid digits entries.	□
	Task requires two-handed actions or switching between input formats (e.g., pressing Shift for symbols, switching between uppercase and lowercase letters).	□
	Input fields or buttons are positioned far apart, requiring stretched hand movement or wide navigation.	□
	Task requires repeated multiple physical actions (scrolling, switching fields, re-typing) to complete input.	□
	Task is difficult or impossible using assistive technologies (e.g., screen readers, switch devices).	□
	Task does not support alternative input methods (e.g., on-screen keyboard, speech, copy–paste).	□
	Total Score	0
Multi-device Interaction (MI)	Task requires switching between devices (e.g., from smartphone to computer) to complete a single security step.	□
	Requires only one verification method (e.g. email, SMS, or app-based authentication) forcing device dependency.	□
	Interrupted or failure a verification method causes entire task failure.	□
	Task requires entering mixed-case characters, digits, or symbols across devices, demanding precise two-hand coordination.	□
	Task demands sustained attention and coordination across devices at once.	□
	Late input or delays cause full task restart; low tolerance for mistakes or slow switching.	□
	Total Score	0
Modality Constraints (MC)	Task relies on a single sensory channel (e.g., visual CAPTCHA without audio or text alternative).	□
	Sensory cues (visual, auditory) are inconsistent or presented in a confusing order.	□
	Lack of alternative output channels prevents completion (e.g., missing audio confirmation or visual indicator).	□
	Task is difficult or impossible to complete using assistive technologies or alternative inputs (e.g., screen readers, speech input, keyboard-only).	□
	No alternative modality options are provided (e.g., no audio version, no text version).	□
	No alternative feedback modalities are available (e.g., no sound cue, no text confirmation).	□
	Total Score	0
Visual Demand (VD)	Task requires visual perception of small, low-contrast, or subtle text or interface elements, increasing visual effort	□
	Task requires sustained visual focus to monitor or interpret visual contents, increasing visual strain.	□
	Task contains visual clutter or poor layout organization, making it difficult to visually locate key elements.	□
	Task uses colour or shape alone to convey key information (e.g., red = error, green = success).	□
	Task is difficult or impossible using assistive technologies (e.g. screen readers, magnifiers, audio output).	□
	Users cannot adjust visual settings (e.g. high contrast, dark mode) or switch to non-visual alternatives (e.g. audio).	□
	Total Score	0
Error Tolerance (ET)	Lockout occurs after few attempts.	□
	Errors cause a full task restart or display misleading results.	□
	Lacks auto-correct features or helpful input suggestions to prevent errors.	□

Dimension	Assessment Criteria (☑ indicates the criterion is applicable)	
	No feedback or unclear overly technical or lack guidance. after incorrect input.	□
	Error messages or alerts are not properly associated with input fields and are not accessible via assistive technologies	□
	No undo or retry options are available without penalty. (e.g. lockout after few attempts).	□
	Total Score	0

Current State of Post-Source Implementation: The Browser Table

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Abstract

Modern web browsers play a crucial role in web accessibility by translating authored content into interactive experiences for diverse users. However, current browsers generally do little to "repair" or remediate inaccessible content post hoc. This paper proposes a methodology to examine how browsers support post-source accessibility augmentation—features that improve accessibility beyond what is provided in the original page source. Such an agenda requires a test corpus consisting of stable, versioned, and publicly available pages that each isolate a single, well-scoped accessibility challenge in minimal HTML/CSS/JS, enabling reliable, repeatable mapping between specific code patterns and accessibility outcomes. WCAG Success Criteria are used strictly as an indexing and isolation mechanism for test targets, not as the evaluative framework for browser responsibility or accessibility sufficiency. A preferred test corpus is curated that supports atomic tests, is mapped to WCAG (Web Content Accessibility Guidelines) Success Criteria, is recognized by the W3C/WAI community (or equivalent expert consensus), and is suited to evaluation of real user-facing browser behavior. This methodology is applied and reveals the beginnings of a "browser table", showing how the browser does augment accessibility, post-source, as part of its role as the user agent.

Introduction

The World Wide Web underpins daily digital activity for most of the global population. From its inception, accessibility requirements were incorporated into web standards. Digital accessibility concerns whether digital content is ultimately rendered and presented in ways that enable people with disabilities—including blind, Deaf, limited mobility, and those with cognitive disabilities—to perceive, operate, understand, and interact with that content.

The web ecosystem has undergone structural transformation. Early web architectures consisted primarily of static code served from a single origin server. Web 2.0 introduced distributed architectures in which third-party services, authorized by the origin site, dynamically inject code and content via JavaScript. Today the most visited sites are mashups of many different services.

User agents evolved in parallel. From early implementations such as Netscape Navigator to contemporary Chromium-based browsers, user agents expanded rendering, scripting, and extension capabilities. Browsers expose APIs permitting both websites and users to install and execute additional functionality. This composable architecture enables a huge and fertile ecosystem. Over 80,000 third-party JavaScript services are available for website owners to add to their sites, providing ads, analytics, social media embeds, payment tools, accessibility widgets, and more [1]. Each also supports an ecosystem of add-ons, with one Web Store stocked with over 200,000 offerings [2]. Third-party JavaScript services (installed by site owners) and extensions (installed by end users) play a research-and-development-like role, validating accessibility-relevant capabilities that may later be integrated into the browser core. Google Lighthouse [3] exemplifies this progression, having originated as an extension and evolved into an automated accessibility audit system built into the browser.

The paper focuses on Chromium-based browsers, which collectively represent nearly 75% of global browser usage [4]. Google Chrome is selected as the reference implementation, as it is the most widely deployed Chromium-based browser and exposes the relevant user-facing accessibility functionality evaluated in this study. Under the hood, Chrome uses the Blink rendering engine [5]

For the purposes of this analysis, the relevant Blink processes are:

1. Load and parse resources (HTML, DOM, CSS, JS and assets) and ultimately render them visually.
2. Build and maintain the accessibility tree. Accessibility data via this data structure are mapped to platform accessibility and downstream assistive technology via operating system APIs.
3. Repeat the above in response to any changes.

Chrome's user interface exemplifies a novice–expert interface, where core functionality is immediately apparent while deeper system layers are available through progressive disclosure. Advanced capabilities within the browser software are organized as layered functionality within a progressive disclosure model, remaining hidden by default and revealed only through deliberate user navigation. The pattern relies on user-initiated disclosure of complexity, allowing expert users to voluntarily surface advanced controls without burdening novice users.

Browser developers have introduced a range of accessibility-oriented capabilities over time. For analytical clarity, these capabilities can be arranged along a rough continuum from passive to active interventions. At the most passive end are tools that provide read-only inspection of internal accessibility representations, such as the DOM, accessibility tree, and ARIA attributes. Progressing along the continuum are capabilities that enable read/write exposure, allowing direct modification of markup and styles, perhaps guided by AI-assisted coding suggestions. These are followed by automated evaluations, including color-contrast checks, and more algorithmically complex rule-based evaluations, such as Lighthouse applying rules mapped to WCAG Success Criteria. At the most complex and programmatically active end of the continuum are forms of programmatic remediation that apply limited, post-delivery augmentations—such as generated text alternatives—with current community discussions considering AI-driven workflows operating over page content [6].

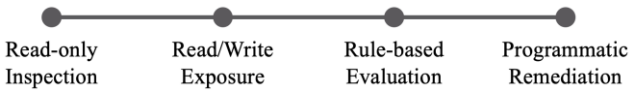


Figure 1 Levels of post-source browser accessibility intervention (from passive to active)

While the typical browser experience is thus a mash-up of a large variety of sources from multiple authors, accessibility governance hewed to a simple source-centered model. W3C guidelines, including WCAG and WAI-ARIA, specify requirements for content authors and assume accessibility coded for, and maintained, by content authors in their source code. This assumption conflicts most notably with the proliferation of visible accessibility widgets—commonly termed "overlays". These source-authorized services modify the rendered content, with some vendors overstating their remediation capability [7]. In parallel, browser extensions capable of detecting WCAG and ACT (Accessibility Conformance Testing) violations continue to proliferate with additional tools providing color contrast modification, font substitution, and text to speech tools [19]. The W3C Community Group report, *Accessibility Capabilities: Post-Source Code and Content*, enumerates approximately seventy accessibility capabilities implementable in the user-agent [8]. These include semantic augmentation, content substitution, and presentation modification applied after DOM construction, and address remediation of the most common challenges on websites: low contrast, missing image alternative description, missing labels on form fields, links without sufficiently descriptive text, buttons without sufficiently descriptive text, and a missing language indicator [9].

This creates a technical question: if post-source accessibility interventions are feasible, why are they not integrated into browser cores? This question aligns with W3C User Agent Accessibility Guidelines [10] and the Internet Architecture Board's directive to prioritize end users [11]. The present study

evaluates the extent to which the browser performs accessibility functions under controlled test conditions.

State of the Art: Accessibility Standards and Testing Frameworks

WCAG defines a set of normative, testable accessibility requirements for web content [12]. These requirements are expressed as technology-agnostic success criteria, and are used to determine conformance at levels A, AA, and AAA. They are referenced in global disability regulations such as the ADA (Americans with Disabilities Act) Title II rulemaking and Section 508 of the Rehabilitation Act in the USA, the EAA and EN 301 549 in Europe, and so on. Some normative test suites are available online for validating various aspects of user-agent behavior [13]. For the purposes of this paper, we required test target pages that feature clearly identified, atomic and isolated accessibility violations that are indexed by WCAG. Two test suites were chosen as most suited, as they isolate semantic conditions so that atomic post-source capabilities can be assessed without dependencies.

1. The ACT Rules Task Force and Community Group [14] harmonize WCAG and WAI-ARIA interpretation for testing. At the time of writing 69 WCAG 2 ACT rules are listed with approximately half approved by the Accessibility Guidelines Working Group. In addition, there are 3 WAI-ARIA ACT rules. Each rule includes structured examples categorized as Passing, Failing, or Inapplicable.
2. Steve Faulkner's HTML5 accessibility test pages [15]. These 133 test cases examine attribute combinations such as *alt*, *title*, and *aria-label* on *img* elements and expose parsing and accessibility-tree mapping behavior.

When suitable atomic test targets are not available in ACT or HTML5 corpora, we draw selectively on additional resources. Web Platform Tests [16] provide a large, community-maintained corpus focused on browser engine correctness, while the VideoJS repository includes targeted test pages well suited to exercising WCAG media success criteria [17]. These sources are not used as primary corpora, as they are not systematically curated around isolated, WCAG-scoped accessibility failures or structured for end-user observational testing across assistive technologies; however, they are valuable for complementary analysis where specific platform behaviors or media controls must be examined.

Methodology

The test environment consists of a Windows operating system host running the Google Chrome browser. Test targets are drawn from the defined corpora. The procedures evaluate browser-native behavior only; no extensions, overlays, or other pre-packaged scripts are installed. Where a test involves screen-reader interaction, NVDA is used with default verbosity and speech settings, with any deviations explicitly logged.

Testing follows a defined navigation sequence crafted to surface the accessibility challenge under test. This includes standard arrow-key navigation, focus navigation using Tab, and—-where applicable—-screen reader single letter navigation (e.g., headings, graphics, links, and form controls). Testers record observable behavior, the announced output where present, and the presence of silence (no announcement) when significant. Screen recording, keyboard input visualization, and NVDA Speech Viewer output are enabled to support traceability and post hoc verification. Where environmental instability occurs (e.g., crashes or corrupted output), the test is repeated once; unresolved ambiguity is explicitly recorded rather than inferred. No attempt is made to correct output, infer author intent, or assume expected results based on metadata; only directly observable browser and assistive-technology behavior is recorded.

Browser Table

Table 2 presents an illustrative excerpt of the proposed Browser Table, showing example results produced using the procedure defined in this paper. Because the present submission is a time-bounded pilot, only a small subset of post-source capabilities is reported here; the intent is to demonstrate how the table is populated rather than to provide a complete inventory.

Table 1 Browser Table of Post-Source Accessibility Augmentation, Excerpt

Post Source Capability	Manual Augmentation?	Automated Evaluation?	Automated Remediation?	Comments
Provide Font Choices	Yes	n/a	n/a	Reading mode offers 9 font face options.
Optimize Text Spacing	Yes	n/a	n/a	Reading mode offers 3 letter spacing options.
Auto-play Videos	Yes	n/a	n/a	Global media controls can pause, play.
Optimize Line Height	Yes	n/a	n/a	Reading mode offers 3 line height options.
Read Content Aloud	Yes	n/a	n/a	Reading mode offers 8 voices, adaptive highlighting, and 6 speeds.
Optimize Color Contrast	Yes	Yes	No	Reading mode offers a wide range of color themes.
Provide Alternative Text	n/a	Yes	Yes	Computer vision returns an accurate description, but may lack context.

Each post-source accessibility capability occupies a single row 7 [8]. The columns characterize the support enabled by the browser, ordered roughly from left to right in accordance with the continuum shown in Figure 1.

A separate column for the most passive capability of "read-only inspection" is omitted for the following reason. Contemporary browsers provide extensive facilities for inspecting accessibility-relevant structures including the accessibility tree, DOM, CSS, ARIA, and semantic HTML. Although this read-only access is a critical architectural prerequisite for all higher-order interventions, it is treated as a baseline capability and therefore implicit.

The *Manual Augmentation* column corresponds to read/write exposure and records cases where accessibility can be improved through deliberate human action. This includes end-user interfaces such as Global Media Controls, as well as methods for adjusting CSS via browser tools (though any modifications that resemble extensions or third-party script injection are considered out of scope). The *Automated Evaluation* column captures instances where built-in browser functionality can audit for the related WCAG-scoped accessibility deficit without altering authored content. The *Automated Remediation* column represents the most active end of the continuum, indicating programmatic interventions in which the browser dynamically behaves—such as rule-driven or AI-assisted augmentation—rather than merely exposing or diagnosing the issue.

Cell values of *Yes*, *No*, and *n/a* indicate whether the browser demonstrably supported the post-source capability at the corresponding level of intervention. *Yes* denotes that support was observed by the tester; *No* denotes that no such support was observed; and *n/a* denotes that the level of intervention is inapplicable for the capability under test (for example, where no meaningful automated evaluation can contribute to the post-source capability cited).

The *Comments* column records qualitative detail that cannot be reduced to a single marker. This includes partial improvements, remaining user-impacting limitations, variability in assistive-technology output, or divergences between expected and observed behavior. Together, this structure reflects an intentional shift away from binary claims of WCAG conformance toward documenting incremental post-source support, prioritizing consistency, reproducibility, and user-experienced impact over absolute pass/fail assertions.

Test targets were used as follows (URL followed by the post source capability tested):

1. https://wpt.live/text-emphasis-line-height-001-ref.html; Provide Font Choices, Optimize Text Spacing, Optimize Line Height, Read Content Aloud.
2. https://videojs.github.io/autoplay-tests/plain/attr/autoplay.html; Auto-play Videos.
3. https://w3.org/WAI/content-assets/wcag-act-rules/testcases/afw4f7/eaf0a926896f045a498073da42ea6263a4d6d36c.html; Optimize Color Contrast.
4. https://w3.org/WAI/content-assets/wcag-act-rules/testcases/46ca7f/e136a03c52c01c1b190c7372d83463f3c6502de9.html; https://stevefaulkner.github.io/AT-browser-tests/test-files/img-alt.html; Provide Alternative Text.

The present submission reports a pilot instantiation of the Browser Table rather than a completed inventory. Empirical results are therefore limited in breadth (including only a small subset of candidate capabilities), and the study does not yet include user participation or user-centered validation. Some test targets were reused, where others might be found to be more precisely suitable.

Conclusions and Next Steps

Existing discourse on post-source accessibility remains largely non-normative, legal, or opinion-driven. Critiques tend to focus on vendor claims, ethical positioning, or conformance philosophy, while promotional materials emphasize theoretical capability. What has been missing from this discussion is a systematic, implementation-level account of what mainstream browsers already do, what they partially support, and what they do not implement at all. The Browser Table is intended to address this gap.

This methodology makes that approach operational. It defines a normative and publicly available set of test targets, something lacking in previous studies [18], and essential to surface observable, user-facing browser behavior under reproducible conditions. Applied even in pilot form, this methodology demonstrates how post-source accessibility capabilities can be decomposed and assessed on a capability-by-capability basis, producing empirical evidence rather than position statements.

The present work reports only a partially completed Browser Table. Subsequent work can complete the table across the full set of identified post-source capabilities and incorporate user studies to assess end-user impact where browser-native augmentation is observed. As the table is extended, it enables clearer distinctions between theoretical feasibility and implemented functionality, clarifies which post-source accessibility functions are already native to browsers, and provides a reproducible reference for browser vendors, standards bodies, policymakers, and accessibility practitioners.

Post-source accessibility is frequently conflated with specific classes of third-party tools, including those commonly described as "overlays." This conflation obscures a more basic question that may better motivate our policies: which accessibility functions are currently fulfilled, in whole or in part, by contemporary user agents, and which remain externalized? A completed Browser Table does not resolve debates about desirability, responsibility, or liability. It instead establishes an empirical baseline against which such discussions can proceed, grounded in observed browser behavior rather than assumption or abstraction.

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