



# **SMART ACCESSIBILITY 2026**

The Eleventh International Conference on Universal Accessibility in the Internet of  
Things and Smart Environments

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Venice, Italy

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# SMART ACCESSIBILITY 2026

## Forward

The Eleventh International Conference on Universal Accessibility in the Internet of Things and Smart Environments (SMART ACCESSIBILITY 2026) was held between May 24, 2026, and May 28, 2026, in Venice, Italy.

There are several similar definitions for universal accessibility, such as design for all, universal design, inclusive design, accessible design, and barrier free design. These and similar approaches are relevant to this conference. The focus will be on methods, tools, techniques and applications for human diversity, social inclusion, and equality, enabling all people to have equal opportunities and to participate in the information society.

The accepted papers covered topics such as accessibility by design, digital inclusion, accessibility devices, and applications. We believe that the SMART ACCESSIBILITY 2026 contributions offered a large panel of solutions to key problems in areas of accessibility.

We take here the opportunity to warmly thank all the members of the SMART ACCESSIBILITY 2026 technical program committee, as well as all the reviewers. The creation of such a high-quality conference program would not have been possible without their involvement. We also kindly thank the authors who dedicated time and effort to contribute to SMART ACCESSIBILITY 2026. We truly believe that, thanks to all these efforts, the final conference program consisted of top-quality contributions. We also thank the members of the SMART ACCESSIBILITY 2026 organizing committee for their help in handling the logistics of this event.

We hope that SMART ACCESSIBILITY 2026 was a successful international forum for the exchange of ideas and results between academia and industry for the promotion of progress on universal accessibility.

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# Accessibility in Medical Devices: Proposal for a Conceptual Framework and Strategies for Universal Design

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**Abstract**— The lack of accessible medical devices is one of the factors that lead to disparities in healthcare services. Accessibility must be embedded throughout the entire lifecycle of Health Technology Management to meet the needs of a diverse patient population encompassing different abilities, limitations, genders, races, ethnicities, cultures, and geographical contexts. This work aims to realize a rapid review of the literature in search of evidence as well as provide proposal framework and strategies for inclusive design in medical devices. This research found a large number of accessibility problems involving different types of medical devices, as well as the lack of accessible technologies in healthcare environments. Different actions to provide a more inclusive and accessible health technology management throughout the life cycle were proposed, such as incorporating user-oriented development, training and development of standard operating procedures.

**Keywords**-Accessibility; Medical Devices; Health Technology Management.

## I. INTRODUCTION

Health technologies consist of medical devices, medications, vaccines, procedures, and systems, developed to solve a health problem and improve quality of life [1]. Considering accessibility aspects in the development of medical devices is essential to ensure inclusion and facilitate the safe use of technologies by a wide range of patients, from those with advanced technological skills to those with no aptitude at all [2]-[3]. Accessibility enables inclusion for people who may temporarily have some limitation or those who have a permanent one [4].

According to data from the World Health Organization, it is estimated that 1.3 billion people suffer from significant disabilities. This represents 16% of the world's population. This number is growing due to the increase in non-communicable chronic diseases and longer life expectancy. Alarming studies indicate that people with disabilities die earlier, have poorer health, and experience more limitations in daily functioning than others [5].

Accessibility, as defined by ABNT (Brazilian Association of Technical Standards) 17060:2022, consists of "the extent to which products, systems, services, environments, and installations can be used by people from

a population with the widest variety of characteristics and capabilities, to achieve a specific objective in a specific context of use" [6]. The objective of accessibility is to expand the target population by ensuring that products, systems, services and environments are usable by a broader range of individuals across diverse contexts of use.

Accessibility aims to design products that meet the needs of a wide range of people, including those with physical, sensory, and cognitive disabilities, whether present from birth or acquired throughout life, as well as older adults with reduced capabilities, individuals with temporary impairments, among others. With the purpose of enabling the broadest possible access for users regardless of skill level, language, culture, environment, or disability, universal design becomes a framework to develop products to be used by all people, without the need for adaptation or specialized design [7]-[9].

Accessibility is determined by the ease of access to the necessary products to achieve the goal for people with the widest variety of abilities [10]-[11] and should be included as part of human-centered design, so that the population that can use technologies effectively, efficiently, and satisfactorily can be expanded, and consequently, usability for all users can be increased [10].

People with disabilities face barriers in all aspects of the healthcare system, such as: lack of knowledge, negative attitudes, and discriminatory practices among healthcare professionals; inaccessible health facilities and information; and lack of information or collection and analysis of data on disabilities contribute to the health inequalities faced by this group [5].

People with disabilities are more affected by health emergencies compared to people without disabilities, due to structural factors, social determinants, risk factors, and health systems, which include health technologies [12]. The global report on health equity for people with disabilities states that, due to systemic and persistent health inequalities, many people with disabilities are at risk of dying up to 20 years earlier than people without disabilities [5].

People with disabilities often do not have the opportunity to receive quality healthcare and sometimes have access to insufficient healthcare [13]. As technologies become increasingly present in the healthcare sector and are

incorporated to assist users in their safer and more reliable use, considering accessibility aspects in technological development becomes a fundamental requirement to achieve product usability [1]. The incorporation of principles that consider usability and accessibility should be strategic business objectives, as they are essential to optimising performance, minimising undesirable consequences for humans, maximising the well-being of the entire organisation, and improving customer relationships [10].

Recent studies in the field of medical devices have prioritized usability and safety as fundamental pillars of technology management, aiming to mitigate operational errors and ensure clinical efficacy. However, as demonstrated in a previous systematic review focused on the state of the art in accessibility, there is a critical scarcity of scientific evidence addressing the inclusion of users with physical, sensory, or cognitive disabilities in the design of this equipment. This methodological gap in the multidimensional analysis of accessibility underscores the need for new evaluation models, such as the use of Living Labs, to integrate the perspectives of diverse users into inclusive design [14].

Due to the importance of considering accessibility to ensure the inclusion of all people in the use of medical equipment, this work aims to realize a rapid review of the literature in search of evidence as well as provide proposal framework and strategies for inclusive design in medical devices.

The rest of the article is structured as follows. In Section II, we discuss the methodology used in the research. In Section III, the results are elucidated. In Section IV, we discuss the results found. Section V concludes the work with a summary and future research directions.

II. MATERIALS AND METHODS

This work was conducted in two stages. The first step consists in exploring accessibility in medical devices with a rapid literature review, which consists of a reliable and systematized methodology to synthesize knowledge. This approach is used when steps in the process of a systematic review are simplified to produce information from the selection of research that is available in the literature, and that is relevant to a study topic [15]. The constant increase in the amount of research carried out in the literature requires the implementation of an approach to evaluate published studies and contribute to decision-making, and thus provide an updated summary of the state of knowledge [16]. The conduct of this rapid review was based on the Methodological Guideline of the Ministry of Health for the preparation of systematic reviews [17], as well as on the PRISMA methodology of the University of Oxford, which consists of a set of evidence-based items that aim to assist in the presentation of research results. The guiding question of the rapid review research proposed for this case study was: **“What is the evidence of accessibility in medical devices?”**

To answer this question, the search strategy used was through the definition of keywords to identify publications that respond to this theme. The use of the logical operators “AND” and “OR” helped in the literature search. The search

in the databases was executed using the union of keywords: (“medical device” OR “medical equipment” OR “health technology”) AND (“accessibility” OR “disabled people” OR “disabled person” OR “disability”) during March 2026. The search was implemented in the following electronic databases: IEEE *Xplore* and Pubmed, which were used systematically. To determine the choice of articles, inclusion and exclusion criteria were established, which included population parameters of the intended technology, the type of intervention used, the availability of the work, the date of publication and the type of evaluation of the results. After the initial search, the date of publication, the titles and abstracts were read, selecting a total of 15 publications. Table 1 explains the number of articles found per database using keywords.

TABLE I. NUMBER OF ARTICLES FOUND PER DATABASE.

Database	(“medical device*” OR “medical equipment*” OR “health technolog*”) AND (“accessibility” OR “disabled people” OR “disabled person” OR “disability”)	(“medical device*” OR “medical equipment*” OR “health technolog*”) AND (“accessibility” OR “disabled people” OR “disabled person” OR “disability”)	(“medical device*” OR “medical equipment*” OR “health technolog*”) AND (“accessibility” OR “disabled people” OR “disabled person” OR “disability”)
Pubmed	124,221	524,172	4,191
IEEE Xplore	18,086	36,081	315

The second stage of this work was to propose a conceptual framework about accessibility in medical devices categorized into different domains. Strategies for inclusive design were shown to improve the accessibility in medical devices for everyone.

III. RESULTS

The results obtained in the rapid literature review highlighted accessibility issues in different types of medical devices, such as examination tables [18]-[20], scales weight [21]-[22], nebulizers, glucometers [23]-[24], positive airway pressure devices [25]-[26] neuromodulation devices, subcutaneous electrode that records the EEG [27] and mammograms [28]. The usability techniques applied to explore and investigate the problems were: questionnaires, interviews, focus groups, and usability tests.

In the studies analyzed, it was found that medical devices are often not accessible to the entire population. Story et al. highlighted the problems faced by patients with disabilities who experience difficulties in using different types of medical equipment [13]. The four main pieces of equipment with the most reported problems were tables, radiology equipment, rehabilitation and exercise equipment, and scales weight. Possible physical damage and incorrect reading of displayed values were the most recurring problems, followed by physical positioning and patient transfer in medical equipment [13]. In Table 2, a description

of accessibility issues in medical devices found during the conduct of the Rapid Literature Review is shown.

In the studies analyzed in the rapid review, a scarce amount of research highlighting accessibility issues in medical devices was found. No evidence was found that considers the perspectives of different actors and stakeholders on accessibility, nor evidence with a methodology for incorporating accessibility throughout the entire lifecycle of technologies, from the development phases to use and obsolescence, as will be presented in the

next section. Medical devices are designed for the benefit of the population; however, they must be accessible to meet the diverse needs of the entire population, considering different ethnicities, races, genders, disabilities, as well as various contexts and locations. Due to the absence of an integrative definition in the current literature, this work proposes a Conceptual Framework for accessibility in medical devices, based on the convergence of 6 essential domains, shown in Figure 1.

TABLE II. SUMMARY OF ACCESSIBILITY ISSUES IN MEDICAL DEVICES FOUND IN THE RAPID LITERATURE REVIEW

Medical Device	Accessibility Issues	Effect
Diabetes Technologies	Screens and parts of the device with low contrast; absence of speech output; small screen and high levels of reflection	Erroneous administration of medications; imprecise diagnosis; hypoglycemia; hyperglycemia
Pulse Oximeter	Lower accuracy and greater bias in patients with dark skin, Asians, and Indigenous people, compared to white patients, increasing racial and ethnic disparity	Overestimation of oxygen saturation
Scale Weight	Absence of accessible scales; patient positioning, location and readability of the display, scale capacity; lack of color differentiation and absence of contrast	Healthcare professionals often ask patients to estimate their own weight, which can lead to health implications
Dental Unit (Dental Chair)	Difficulty in transfer; maintaining balance during the procedure; unable to support weight for obese patients; excessive height; intrusive arm position, lack of support devices, coating material, and lack of skill from the team in transfer and positioning process	Patient falls; discomfort; in some cases, chemical and/or physical restraints are used to ensure adherence and immobility
Imaging Diagnostic Equipment	Contact surfaces, transfer support, and positioning support; inability to bring wheelchairs or scooters into the MRI room (due to the magnetic field); equipment capacity	Inability to perform exams and not diagnose diseases; interruption in patient care
Woman Health Technology	Difficulty in maintaining positions during gynecological exams; examination tables and auxiliary components do not provide support to maintain proper positions; lack of adjustable height	Lower likelihood of undergoing preventive exams; patient fall

Beyond operational accessibility, there is also economic accessibility, which refers to the ability of individuals to afford healthcare without experiencing financial hardship. Social and cultural accessibility must also be considered, since factors such as language, age, gender, ethnicity, or religion may discourage the pursuit of healthcare services. Another dimension of accessibility is spatial, which assesses the distance or travel time between the user’s location and the healthcare service, potentially affecting access to care. Geographic accessibility, such as in rural, remote, or conflict zones, poses additional challenges for users. Populations in these areas must cope with unique safety threats that may further obstruct physical access. Informational accessibility represents another dimension, defined as the dissemination of health information in a manner that is accessible and

understandable to all users, enabling them to benefit from it and achieve their full health potential.

Therefore, accessibility in the context of medical devices could be defined as technologies that can be used, operated, accessed, and experienced by the greatest possible number of people, considering diverse abilities, cultures, characteristics, and geographic locations. In this project, accessibility will be characterized across six dimensions: operational, economic, sociocultural, infrastructural and spatial, informational and connectivity ad data, as shown in Figure 1.

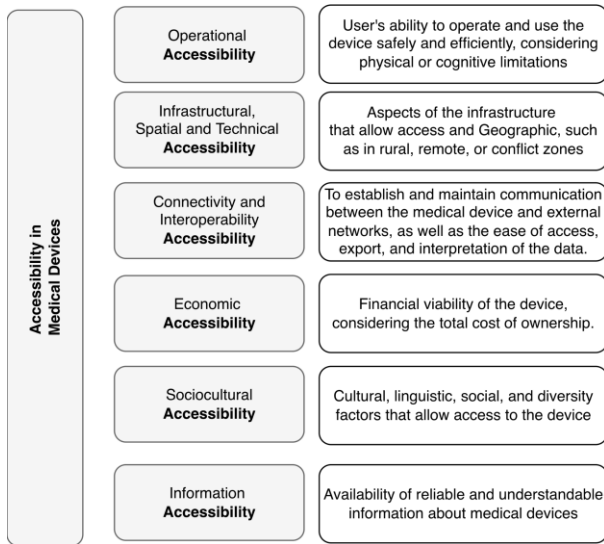


Figure 1. Dimensions of accessibility in medical devices.

Based on the proposed domains, we propose the following strategies for universal design of medical devices.

- **Operational Accessibility:** Inclusive Co-design, engaging multi stakeholders throughout the development process; Multimodal Interfaces, integration of auditory, tactile, and visual feedback; Assistive Technology Compatibility, ensuring seamless interaction with external assistive devices; Visual Ergonomics, contrast, font scaling, and display readability; Critical Action Redundancy, allowing essential tasks to be performed via multiple methods; Haptic Feedback, implementing tactile vibrations to confirm user actions or device status.
- **Economic Accessibility:** Cost-Benefit Optimization, Total Cost of Ownership Analysis, designing for essential functionality to ensure safety and reliability in resource-constrained settings; Reverse Logistics, implementing sustainable take-back and recycling programs for medical devices.
- **Infrastructure, Technical, and Spatial Accessibility:** Anthropometric Adaptation, designing for a wide range of body sizes and physical abilities; Versatile Portability, ensuring functionality across home care, clinical, remote, and conflict zone environments; Environmental Resilience, robust design protected against dust, water, humidity, and mechanical drops; Power Autonomy, ensuring device operation in areas with electrical instability or intermittent power; Spatial Optimization, compact footprints that do not obstruct emergency exit routes or clinical workflow; Universal Mounting, designing rails, brackets, and connectors compatible with international medical standards.
- **Connectivity and Interoperability Accessibility:** Standardized Protocols, adoption

of interoperable communication standards (e.g., Health Level Seven International (HL7), Digital Imaging and Communications in Medicine (DICOM); Cybersecurity by Design, integrating data protection and encryption from the earliest stages of development; Workflow Integration, facilitating seamless data synchronization with Electronic Health Records (EHR); Offline-First Functionality, ensuring full device operation and local data storage during internet outages, with automated synchronization upon reconnection.

- **Informational Accessibility:** Inclusive User Manuals, providing instructions via audio-described videos, Braille, and plain language (Easy-to-Read); Digital Accessibility Compliance, ensuring apps and platforms follow global standards like Web Content Accessibility Guidelines (WCAG); Health and Digital Literacy, empowering users to understand and manage their health data effectively; Accessibility Education, promoting training and awareness regarding inclusive design in medical technology.
- **Sociocultural Accessibility:** Cultural and Linguistic Localization, adapting interfaces and terminology to local languages and social norms; Lifestyle Integration, adapting devices for daily activities, such as bathing, exercising, and social interaction; Stigma Mitigation, reducing the "clinical look" of devices through aesthetic design that resembles common accessories or clothing (Wearables); Algorithmic Equity: ensuring sensors perform accurately across different skin tones and body compositions, preventing technological bias.

## VI. DISCUSSION

According to the account of one of the users in the research conducted by Story et al., "more than ramps are needed to solve the health crisis for people with disabilities" [13]. It is necessary to manage technologies focused on population diversity through user involvement. Accessibility must be incorporated into various phases of new technology, as well as in planning, acquisition, verification, training, use, decommissioning, and other activities throughout all life cycles, by applying Universal Design as a strategy and including people of all ages and abilities throughout the technology lifecycle. Universal design aims to create products in an accessible manner, in a simple and intuitive way, with equal possibilities of use [6].

In the pre-market, the lack of inclusion of user diversity in the design and validation of medical devices can result in performance issues for these devices for individuals of certain population profiles, thus perpetuating structural inequalities in healthcare. As presented by Jamali, the evidence highlights the need to include diverse patient populations in the design and validation of medical devices [29]. Biased data used in the development of medical technologies is a common cause of performance variation among racial and ethnic

groups [30]. Although design flaws may largely be unintentional, every effort should be made to identify, mitigate, and remove these biases so that they do not contribute to significant health disparities in minority groups [30]. Interdisciplinary involvement is also important in the process of incorporating new technologies, in order to ensure that the incorporated technology meets the diversity of the population.

To mitigate accessibility issues in medical devices, different stakeholders must be involved. Some actions and recommendations include: conducting continuous training to raise awareness among healthcare professionals about the accessibility issues faced by medical devices; improving regulatory requirements for devices; developing standard operating procedures considering accessibility at each stage of the technology lifecycle; and considering population diversity in the technological development process by applying the living lab methodology [31]. Therefore, developing user-centered technologies embedded in an interdisciplinary Living Lab, considering aspects of usability and accessibility, constitutes a recommended approach to explore problems and establish actions for improving the design and use of technologies.

It is necessary to develop technologies focused on population diversity through the involvement of users from the initial design process of medical equipment. Continuously carrying out training with the entire team and developing standard operating procedures are other strategies to be implemented by Clinical Engineering together with other actors in order to establish a more accessible healthcare environment. In the pre-market stage of medical device development, the lack of inclusion of user diversity in the design and validation of medical devices can result in performance problems of these devices for individuals from certain population profiles, thus perpetuating structural inequalities in medical care. As presented by Jamali, evidence highlights the need to include diverse patient populations in the design and validation of medical devices [30] as biased data used to develop medical technologies is a common root cause of performance variation between racial and ethnic groups [30]-[32].

#### V. CONCLUSION AND FUTURE WORK

This work highlighted accessibility problems involving medical devices. Through a rapid review of the literature, it was found that most technologies are inaccessible and/or absent within healthcare environments. Accessibility must be embedded into the technological life cycle, beginning with the initial design phase. Furthermore, the limited existing literature on accessibility in medical devices highlights an urgent need for research that incorporates diverse user profiles to ensure inclusive medical devices. To address this evidence gap, the Institute of Biomedical Engineering (IEB-UFSC) plans to conduct future studies within its Living Lab ecosystem. By applying usability techniques, this initiative will foster an interdisciplinary and collaborative health ecosystem multi-stakeholders,

engaging patients, healthcare providers, manufacturers, and clinical engineers, to identify accessibility challenges and develop strategies for more inclusive and human-centered medical devices.

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# Rethinking Digital Exclusion: Interaction Design Barriers in Adults with Intellectual Disabilities

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**Abstract**— Digital exclusion of individuals with Intellectual Disabilities (ID) persists despite improvements in technical accessibility standards. In digital literacy approaches, participation barriers are often attributed to a lack of skills rather than to the interaction patterns embedded in digital systems. However, there has been limited empirical investigation of how such patterns hinder engagement in real-world settings. To address this question, a nine-month exploratory field study was conducted within a semi-structured digital literacy program involving four adults with intellectual disabilities. Participants attended 32 weekly sessions using custom-designed training games. Data were collected through structured field notes, reflective logs, and in-game observations. The study showed recurring interaction breakdowns across participants, clustering into five categories: precision-dependent interactions, structured input and memory reliance, visual discrimination overload, text interaction complexity, and voice interface misalignment. While some adaptation occurred, persistent breakdowns required simplified interaction models. These findings suggest that digital exclusion reflects systemic interaction assumptions rather than solely a literacy deficit, and that some barriers cannot be resolved through training alone.

**Keywords**— *cognitive accessibility; intellectual disabilities; interaction design; usability barriers; digital literacy; digital inclusion.*

## I. INTRODUCTION

Digital participation is essential for social inclusion, employment, and independent living; however, individuals with intellectual disabilities remain disproportionately excluded from digital environments. Accessibility research has largely focused on sensory and physical impairments, while cognitive accessibility remains underexplored [1].

Digital literacy training programs often assume that increased familiarity with technology will reduce exclusion. However, such approaches frequently rely on a “deficit model” [2], teaching users to adapt to existing systems rather than questioning whether those systems are inherently accessible. As Bacalja et al. [3] argue, focusing solely on functional competency ignores the embedded design assumptions of technology and risks preparing users to be passive consumers of systems that were not built with their needs in mind. Consequently, learning outcomes remain limited, and acquired skills may not effectively transfer to real-world digital environments where underlying interaction barriers remain unaddressed.

Similarly, established approaches such as Universal Design [4] and Web Accessibility Standards [5] (e.g., Web Content Accessibility Guidelines (WCAG) 2.1) have improved general access, yet they often remain insufficient for addressing the specific cognitive and motor interaction challenges faced by people with intellectual disabilities [6]. While these standards focus on technical compliance, they frequently overlook the cognitive load and temporal precision embedded in standard interface metaphors, which may remain exclusionary regardless of user familiarity.

Prior research has identified interaction challenges such as navigation difficulty, input precision, and information processing [1]; however, these are typically framed as individual deficits rather than systemic design constraints.

Building on prior work introducing a semi-structured digital literacy program at DIGI Lab Siegen [7], longitudinal observations revealed that certain interaction breakdowns persisted despite repeated training and adaptation.

This challenges a core assumption of digital inclusion efforts: that increased exposure and practice are sufficient to overcome barriers.

This study, therefore, addresses the following questions:

- 1) *How do interaction patterns embedded in digital systems hinder engagement for adults with intellectual disabilities in real-world settings?*
- 2) *To what extent are persistent interaction barriers a result of systemic design patterns rather than limitations in digital literacy?*

## II. METHODOLOGY

A nine-month exploratory field study was conducted with four adults (aged 40–62) with intellectual disabilities participating in a semi-structured digital literacy program. Participants attended 32 weekly sessions combining guided instruction, custom-designed training games, and real-world tasks.

Custom interactive games were developed to isolate specific interaction components (e.g., clicking precision, drag-and-drop, text input), enabling targeted observation of interaction breakdowns.

Data were collected through structured field notes, reflective logs, and in-game observations. Interaction barriers were identified based on repeated failure, assistance requests, or task abandonment. Patterns were analyzed longitudinally to distinguish between temporary learning effects and persistent breakdowns.

### III. RESULTS AND CONSIDERATIONS

Across participants and sessions, five recurring categories of interaction breakdowns were identified:

#### 1) Precision-dependent interactions

Persistent difficulties were observed in tasks requiring temporal accuracy and fine motor control, including double-clicking, drag-and-drop operations, and interaction with small interface elements. Participants frequently demonstrated inconsistent click timing or prolonged button presses, resulting in unsuccessful activation. Modifications replacing double-click interactions with single-click or keyboard-based alternatives led to immediate reductions in error frequency.

#### 2) Structured input and memory reliance

Systematic errors were observed in tasks involving structured text input. These included sequence compression, inconsistent handling of repeated characters, and reduced sensitivity to spatial separation within text. These patterns indicate reliance on working memory and implicit segmentation processes embedded in conventional input design.

#### 3) Visual discrimination overload

Interaction breakdowns were associated with perceptual demands, particularly in cases involving low visual contrast, color similarity, or weak focus indicators. Participants demonstrated difficulty reliably identifying target elements, occasionally selecting adjacent areas rather than intended targets. These effects suggest combined perceptual and motor interaction constraints.

#### 4) Text interaction complexity

Tasks requiring precise cursor placement, such as text selection, resulted in repeated unsuccessful attempts. Additionally, participants showed reduced retention of multi-step instructions, frequently recalling only the final segment. This indicates increased cognitive load associated with both motor precision and sequential information processing.

#### 5) Voice interface misalignment

Speech-based interaction systems demonstrated limited robustness to atypical speech patterns, including delayed onset, pauses, and socially embedded language. In the absence of confirmation mechanisms, misrecognition led to repeated errors and reduced user confidence.

Across categories, several breakdown patterns were observed in three out of four participants and recurred across multiple sessions. While partial improvement was noted, key interaction difficulties—particularly those involving precision and structured input—persisted despite repeated exposure, guided support, and task repetition. In multiple instances, participants were able to complete tasks under guided conditions but were unable to reproduce the same actions independently in subsequent attempts. This suggests that task completion did not necessarily correspond to stable skill acquisition.

Importantly, when interaction structures were modified—such as simplifying input requirements or reducing precision constraints—task success rates increased immediately. These modifications did not alter task outcomes but instead

provided alternative pathways to achieve the same result. For example, in a mouse-control activity, one participant repeatedly missed small clickable targets despite understanding the task goal. After the target area was enlarged and the interaction was changed to a single-click action, the participant completed the same task with fewer errors and less assistance. This indicates that many conventional interaction requirements are not intrinsic to task completion but rather reflect established design conventions.

Overall, the observed breakdowns were consistently linked to specific interface patterns rather than to lack of exposure alone. Furthermore, the persistence of these breakdowns despite repeated training, combined with immediate improvement following interaction simplification, indicates that these barriers are primarily rooted in systemic design patterns rather than limitations in digital literacy. However, due to the exploratory design and the small participant group of four adults, the findings should be interpreted as indicative patterns rather than statistically generalizable results.

### IV. CONCLUSION

This study demonstrates that digital exclusion cannot be fully explained by limited digital literacy but reflects a mismatch between human cognitive variability and standardized interaction design. The findings suggest that cognitively accessible systems should reduce reliance on motor precision, structured input, and implicit perceptual distinctions. Future work should build on these exploratory observations through controlled usability studies, prioritizing interaction categories that persisted across sessions and improved after simplification. Such studies could compare conventional and simplified interaction models while systematically recording errors, assistance requests, task completion, and independent repetition.

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# Embedding Accessibility into National Building Regulations: The Omani Building Code Experience

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**Abstract** - Accessibility in the built environment is widely recognized as a fundamental component of inclusive, safe, and sustainable environments. However, in many national contexts, accessibility principles are still not translated into enforceable regulatory frameworks. This paper examines how accessibility has been embedded within the recently adopted Omani Building Code (OBC) as part of a unified national regulatory system. Using a qualitative, policy-oriented case study approach, the analysis focuses on the structure of the accessibility framework, its integration across related regulatory provisions, and the phased enforcement strategy supporting implementation. The paper argues that the OBC represents a structured regulatory model that transforms accessibility from voluntary design consideration into a legal obligation. It identifies three key features of this model: a dedicated accessibility chapter, alignment with international technical standards, and a gradual transition toward mandatory enforcement. The Omani experience offers transferable policy insights for Gulf countries and other developing contexts seeking to institutionalize accessibility through clear, enforceable, and adaptable building regulations.

**Keywords** - *Accessibility; Universal Design; Building Regulations; Policy Framework; Built Environment; Phased Implementation; Gulf Countries.*

## I. INTRODUCTION

Accessibility in the built environment is widely recognized as a foundational element of inclusive and sustainable development. It enables persons with disabilities, older persons, and individuals with diverse mobility needs to access buildings, public spaces, and services safely and independently [1][2]. Beyond its social dimension, accessibility also contributes to usability, safety, and resilience of the built environment for all users [1]. Despite this broad recognition, accessibility remains unevenly realized across many national contexts, particularly where regulatory frameworks lack clear, enforceable requirements and consistent implementation mechanisms [3].

At the urban scale, universal design is increasingly framed as a guiding principle for inclusive cities, where access to the built environment is understood not as a specialized feature, but as a core requirement for equitable participation in daily life [4].

However, in many countries, accessibility has traditionally been addressed through voluntary guidelines, design manuals, or sector-specific policies. While such instruments play an

important role in raising awareness and providing technical guidance, they often lack the legal authority necessary to ensure consistent application [3]. As a result, accessibility may be treated as an optional design consideration, vulnerable to budget constraints, time pressures, or subjective interpretation during project delivery. This gap between policy intent and regulatory enforcement continues to limit the effectiveness of accessibility initiatives worldwide [3].

Building regulations offer a powerful mechanism for translating accessibility principles into enforceable practice. As legally binding instruments, building codes shape design decisions, approval processes, and construction outcomes across both public and private sectors. When accessibility is embedded within a national building code, it becomes an institutional obligation rather than an act of goodwill. This regulatory positioning is particularly significant in rapidly urbanizing and developing contexts, where large-scale construction provides a critical opportunity to mainstream inclusive design from the outset [3].

The Sultanate of Oman has recently adopted a unified national building code that explicitly addresses accessibility within its regulatory framework. The Omani Building Code (OBC) introduces a dedicated accessibility chapter, integrates accessibility across multiple regulatory provisions, and is supported by a structured phased enforcement strategy [5][6]. Rather than focusing on post-occupancy evaluation or technological interventions, the OBC emphasizes regulatory clarity, institutional coordination, and gradual enforcement as the basis for sustainable implementation.

This paper presents the Omani experience as a policy-oriented case study, examining how accessibility can be embedded within national building regulations through regulatory design rather than isolated technical measures. The paper argues that this approach provides a structured model for transforming accessibility from a voluntary design consideration into an enforceable regulatory requirement. It focuses on the structure of the accessibility framework within the OBC, its integration across related regulatory domains, and the rationale behind its phased enforcement strategy.

The remainder of this paper is organized as follows. Section II discusses the role of building regulations in accessibility governance. Section III outlines the methodological approach adopted in this study. Section IV presents an overview of the Omani Building Code. Sections V, VI, and VII examine the accessibility framework, regulatory–technical separation, and integrated accessibility.

Section VIII discusses the phased enforcement strategy. Section IX presents the discussion, and Section X concludes the paper with future work.

## II. ACCESSIBILITY AND BUILDING REGULATIONS

From a policy perspective, accessibility within the built environment is most effective when supported by clear and enforceable regulatory frameworks. While accessibility principles are widely promoted through international conventions, standards, and best practice guidelines, their impact depends largely on how they are institutionalized at the national level [3]. International standards, such as ISO 21542, provide technical guidance to support consistent accessibility implementation in the built environment [7]. In the absence of binding regulations, accessibility requirements are often applied inconsistently, resulting in uneven outcomes across regions, sectors, and building types [3].

Building regulations occupy a critical position in the governance of the built environment. As legally binding instruments, they establish minimum requirements that directly influence planning approvals, design decisions, construction practices, and compliance processes. When accessibility is incorporated into building regulations, it becomes a shared responsibility across the development chain, including policymakers, designers, developers, contractors, and regulatory authorities. This collective accountability distinguishes regulatory approaches from voluntary initiatives, which rely primarily on individual commitment and professional discretion. This highlights the importance of positioning accessibility within formal regulatory systems rather than relying solely on voluntary approaches.

An important challenge in regulating accessibility lies in balancing legal clarity with technical flexibility. To address this, many regulatory systems adopt a layered approach in which national building codes define the scope, applicability, and legal obligations of accessibility, while detailed technical requirements are provided through referenced standards that can be updated more frequently in line with international best practice [8]. In developing and rapidly urbanizing contexts, phased implementation strategies further support enforceability by enabling institutional adaptation, professional training, and market readiness while maintaining regulatory intent [6]. Within this policy context, the Omani Building Code provides an illustrative case of how accessibility can be embedded within national regulations through a structured combination of regulatory definition, technical alignment, and phased enforcement. This approach forms the basis of the analytical framework adopted in this study.

## III. METHODOLOGY

This paper adopts a qualitative, policy-oriented case study approach to examine how accessibility has been embedded within the OBC. The case study method is particularly appropriate for analyzing regulatory frameworks at an early stage of implementation, where the primary interest lies in institutional design, governance structure, and policy logic

rather than measurable performance outcomes. Rather than evaluating the effectiveness of accessibility measures in completed buildings, this study focuses on how accessibility is structured, positioned, and operationalized within national regulation.

The analysis is grounded in a document-based review of official regulatory and policy materials. Primary sources include the accessibility chapter of the Omani Building Code (Chapter 11), the international technical standard referenced by the code (ICC A117.1: Accessible and Usable Buildings and Facilities), and the officially issued phased enforcement plan outlining the gradual implementation of the building code [8][5][6]. These documents were examined to identify the regulatory scope of accessibility, the relationship between national regulations and international standards, and the mechanisms used to integrate accessibility across different code provisions. The analysis is guided by three qualitative criteria: regulatory clarity, referring to how clearly accessibility obligations are defined; technical alignment, referring to the relationship between the national code and international standards; and implementation support, referring to how the transition toward enforceable application is structured through phased enforcement.

This methodology emphasizes regulatory architecture rather than detailed technical assessment. It does not evaluate specific dimensional requirements or compliance measurements. Instead, it focuses on how accessibility is framed as a legal obligation, how responsibilities are distributed across regulatory instruments, and how implementation is structured over time.

The case study is presented as an illustrative example rather than a prescriptive model. While Oman’s regulatory context reflects its specific institutional and legal conditions, the analysis aims to identify transferable policy principles that may inform similar efforts in other Gulf countries and developing contexts.

As illustrated in Figure 1, the analysis is structured around three main criteria guiding the evaluation of the OBC. This approach is applied in the following sections to examine the structure of the OBC and its phased enforcement strategy.

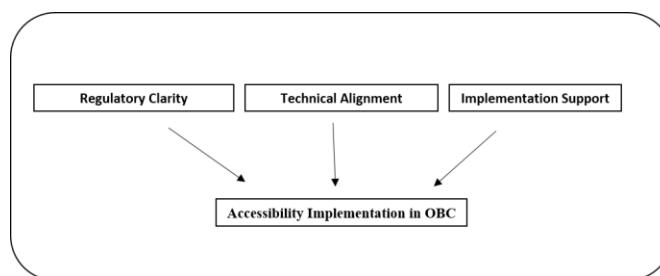


Figure 1. Analytical framework for embedding accessibility within the OBC.

## IV. OMANI BUILDING CODE OVERVIEW

The OBC represents a significant step toward establishing a unified national regulatory framework governing the design, construction, and use of buildings across the Sultanate of

Oman. Developed to address previously fragmented regulatory practices, the code consolidates requirements related to safety, health, usability, and accessibility within a coherent structure. This integration enhances regulatory clarity by providing a single authoritative reference for stakeholders involved in design, approval, and enforcement processes [5].

The adoption of a unified building code reflects a strategic policy shift toward standardization and regulatory clarity. By providing a single reference for building requirements, the OBC supports consistency in interpretation, approval, and enforcement processes, reducing ambiguity for designers, developers, and regulatory authorities. This is particularly important in rapidly urbanizing contexts, where increasing construction activity requires consistent and enforceable regulatory guidance to ensure uniform implementation of accessibility requirements [5].

Within the structure of the OBC, accessibility is not treated as a supplementary or optional consideration but is positioned as an integral component of the broader regulatory system. It is embedded alongside core domains such as fire safety, circulation, and usability, reflecting its role as a cross-cutting element that directly influences both safety and functional performance of the built environment. This positioning reinforces accessibility as a fundamental regulatory requirement rather than a specialized design feature.

The OBC adopts a modular structure, with distinct chapters addressing specific regulatory themes while maintaining coherence across the overall framework. This structure allows accessibility provisions to be defined centrally while being reinforced across related technical domains, thereby improving regulatory consistency and supporting coordination between different regulatory domains [5].

Importantly, the OBC is supported by an officially defined phased enforcement strategy that enables a gradual transition from voluntary adoption to mandatory compliance. This phased approach supports institutional readiness, professional capacity building, and market adaptation, thereby strengthening the implementation support dimension of the regulatory framework. By structuring enforcement over time, the OBC enhances the feasibility and sustainability of accessibility implementation within the built environment.

## V. ACCESSIBILITY FRAMEWORK

Accessibility within the OBC is formally addressed through a dedicated chapter that establishes the regulatory foundation for accessible buildings, sites, and associated facilities. Chapter 11 defines accessibility as a mandatory requirement within the national regulatory framework, reinforcing its status as a legal obligation rather than a discretionary design feature. This positioning enhances regulatory clarity by clearly defining the scope and applicability of accessibility requirements across building types and facilities [5].

Rather than functioning as a purely technical manual, Chapter 11 defines the regulatory scope of accessibility by specifying where it is required and the obligations placed on

stakeholders. This approach ensures that accessibility is treated as a compliance requirement embedded within the regulatory system rather than an optional design consideration.

A key feature of the accessibility framework is its reliance on internationally recognized technical standards to guide implementation. While Chapter 11 establishes regulatory obligations at the national level, detailed technical requirements are not fully embedded within the code itself. Instead, the OBC references ICC A117.1 as the primary technical benchmark for accessibility design [8][5]. This approach reflects a clear separation between regulatory requirements and technical specifications, ensuring alignment with international best practices while maintaining flexibility within the national regulatory framework.

The framework also reflects an understanding of accessibility as a condition that benefits a wide range of users beyond persons with disabilities. While the chapter explicitly addresses accessibility for persons with physical disabilities, its provisions contribute more broadly to usability and safety within the built environment. This reinforces the integration of accessibility within mainstream regulatory practice rather than isolating it as a specialized concern.

By defining accessibility requirements at the level of regulatory principle and scope, Chapter 11 provides a stable foundation for implementation while allowing flexibility in technical application. This structure supports future updates to technical standards without requiring major revisions to the national regulatory framework, thereby enhancing the long-term adaptability and resilience of accessibility provisions within the OBC.

## VI. REGULATORY AND TECHNICAL SEPARATION

A defining characteristic of the accessibility framework within the OBC is the clear separation between regulatory obligations and technical implementation. This separation reflects a deliberate policy design that distinguishes between defining legal requirements and specifying how they are achieved in practice. Within this approach, the OBC establishes when and where accessibility is required, while technical standards define how accessibility is implemented [5][8].

The regulatory role of the OBC lies in establishing accessibility as a binding legal requirement within the national framework. Through Chapter 11, the code defines the scope of application, identifies the buildings and facilities subject to accessibility provisions, and sets enforceable obligations through approval and inspection processes. This ensures that accessibility is treated as an integral component of regulatory compliance rather than a discretionary design consideration [5].

In contrast, ICC A117.1 functions as the primary technical reference for accessibility design, providing detailed specifications related to dimensions, clearances, and configurations required to achieve accessible environments [8]. By referencing this standard rather than embedding detailed technical requirements within the code itself, the

OBC avoids duplication and reduces the risk of technical obsolescence.

This regulatory–technical separation offers several policy advantages. It enables the regulatory framework to remain stable while allowing technical standards to evolve independently. It also supports alignment with international best practices and provides clarity for practitioners by distinguishing between legal obligations and technical solutions. This approach enhances both regulatory clarity and technical flexibility within the accessibility framework.

From an implementation perspective, this separation improves transparency and consistency in regulatory enforcement. Authorities can focus on verifying compliance with defined obligations, while designers and engineers rely on technical standards for detailed design decisions. This reduces ambiguity in interpretation and supports more effective application of accessibility requirements across projects [5][8].

Overall, the regulatory–technical separation embedded within the OBC represents a structured and adaptable approach to accessibility regulation, offering a model that may inform similar regulatory efforts in other jurisdictions.

#### VII. INTEGRATED ACCESSIBILITY

Accessibility within the OBC is not confined to the dedicated accessibility chapter. While Chapter 11 establishes the regulatory scope and legal obligations, accessibility-related requirements are integrated across other code provisions addressing circulation, means of egress, and life safety [5]. This integrated structure reflects an understanding of accessibility as a cross-cutting regulatory principle rather than an isolated technical requirement.

By embedding accessibility-related elements within relevant technical domains, the OBC aligns accessibility with broader objectives of safety, usability, and functional performance. Features such as accessible circulation routes, ramps, and visual alarm systems contribute to safer and more inclusive environments for all users, including people with disabilities, older people, and occupants in emergency situations [5][8]. This approach strengthens regulatory coherence and reinforces accessibility as an integral component of mainstream building regulation.

#### VIII. PHASED ENFORCEMENT STRATEGY

The implementation of accessibility requirements under the OBC is guided by a structured, multi-year phased enforcement strategy that facilitates a gradual transition from voluntary application to mandatory compliance [6]. This phased approach reflects a policy decision to balance regulatory ambition with practical feasibility, particularly in contexts where new regulatory frameworks require institutional and professional adaptation.

Phased enforcement supports implementation by enabling capacity building among regulatory authorities, designers, and practitioners, while also allowing the construction sector to gradually align with new requirements. This reduces the risk

of non-compliance and enhances the overall effectiveness of accessibility provisions over time.

By sequencing enforcement and prioritizing specific building categories, the strategy provides a controlled pathway toward full regulatory implementation. This approach strengthens the implementation support dimension of the framework by ensuring that accessibility requirements are not only defined but also realistically applied within the built environment.

#### IX. DISCUSSION

The Omani experience demonstrates how accessibility can be effectively embedded within national building regulations through a structured combination of regulatory clarity, technical alignment, and phased implementation [5][6][8]. Rather than treating accessibility as a supplementary design consideration, the OBC positions it as a fundamental component of the regulatory system governing the built environment.

This approach highlights the importance of integrating accessibility within formal regulatory frameworks to ensure consistent and enforceable implementation. It suggests that accessibility outcomes can be significantly improved when supported by clear legal obligations, alignment with international technical standards, and structured enforcement mechanisms. These elements are particularly relevant for Gulf countries and other developing contexts, where accessibility commitments often exist but lack effective regulatory enforcement.

At a broader level, the findings of this study indicate that accessibility should not be addressed solely through technical design guidance, but through comprehensive regulatory design that integrates policy, technical standards, and implementation strategies. This perspective contributes to the growing body of research emphasizing the role of governance and institutional frameworks in achieving inclusive built environments [9].

However, the effectiveness of this approach depends on several contextual factors, including institutional capacity, professional awareness, and enforcement mechanisms. While the OBC provides a strong regulatory foundation, its long-term impact will depend on the extent to which these supporting conditions are realized in practice.

#### X. CONCLUSION AND FUTURE WORK

This paper has examined how accessibility can be embedded within national building regulations through the case of the Omani Building Code. The analysis demonstrates that accessibility can be more effectively institutionalized when supported by a structured regulatory framework that integrates legal obligations, technical standards, and phased implementation strategies.

The findings highlight that positioning accessibility as a regulatory requirement, rather than a voluntary design consideration, enhances consistency, enforceability, and long-term sustainability of accessibility outcomes within the built

environment. The separation between regulatory scope and technical implementation further contributes to flexibility and alignment with international best practices.

This study also underscores the importance of implementation support mechanisms, particularly phased enforcement, in enabling institutional readiness, professional capacity building, and gradual adaptation within the construction sector. These elements collectively strengthen the effectiveness of accessibility provisions in practice.

While the Omani experience reflects its specific regulatory context, the principles identified in this study offer transferable insights for other Gulf countries and developing contexts seeking to advance accessibility through national building regulations.

Future research may examine the practical application of the OBC in completed projects, evaluate compliance levels across different building types, and assess user experiences of accessibility within the built environment to further validate the effectiveness of the regulatory approach.

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# AccessAI: Exploring AI-Driven Support for Smart Digital Accessibility Compliance

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**Abstract**—Digital accessibility compliance remains a significant challenge for organizations due to the cost, time, and specialized expertise required for traditional accessibility audits. While automated testing tools such as axe-core and WAVE can identify accessibility violations against the Web Content Accessibility Guidelines (WCAG), they often lack contextual guidance, prioritization, and iterative remediation support. This work-in-progress paper introduces AccessAI, a conceptual AI-driven accessibility auditing framework aligned with Smart Accessibility principles. AccessAI integrates automated accessibility evaluation using established engines, interactive dashboarding for compliance visualization, and conversational chatbot assistants powered by Large Language Models to support continuous compliance. The framework targets perceivable and operable accessibility dimensions under WCAG 2.2 Levels A, AA and AAA, addressing both physical and cognitive barriers to digital inclusion. This paper reviews the state of the art, identifies knowledge gaps, outlines the proposed system architecture with concrete technical details, and describes a three-phase mixed-method evaluation methodology.

**Keywords**—digital accessibility; WCAG compliance; automated evaluation; conversational AI; smart accessibility.

## I. INTRODUCTION

Smart Accessibility emphasizes the use of intelligent, adaptive systems to proactively support inclusive digital experiences [1]. As digital services become increasingly embedded in everyday life, accessibility compliance has become a critical requirement, reinforced by international standards such as the Web Content Accessibility Guidelines (WCAG 2.2), developed by the World Wide Web Consortium (W3C) [2]. Organizations are expected not only to achieve compliance but also to sustain it across continuous updates and iterative development cycles.

Despite growing awareness, accessibility remains difficult to operationalize. Manual audits conducted by accessibility specialists require significant time and expertise, making them costly and difficult to scale across large or frequently changing systems [3]. Existing automated tools such as axe-core [4], WAVE [5], and Lighthouse [6] help identify accessibility violations, but they typically cover only 30–50% of WCAG success criteria automatically [7] and produce static reports that lack sufficient explanation, prioritization, and actionable remediation guidance.

From a theoretical perspective, the limitations of current tools align with challenges identified in Human–Computer Interaction (HCI) research. Studies by Bi et al. [8] and Alshayban et al. [9] have shown that developers frequently struggle with interpreting accessibility audit results and translating them into effective code changes. The absence of contextual, conversational support in existing tools contributes to this difficulty.

AccessAI is proposed as a Smart Accessibility-aligned concept designed to move beyond static accessibility validation. By integrating automated evaluation, interactive dashboards, and conversational AI assistance powered by Large Language Models (LLMs), AccessAI aims to embed accessibility more naturally into modern development processes. The key contributions of this paper are: (1) a review of the state of the art identifying knowledge gaps; (2) a conceptual architecture for an integrated accessibility support framework; (3) a specification of the accessibility dimensions targeted; and (4) a detailed three-phase evaluation methodology.

The remainder of this paper is structured as follows. Section II reviews related work. Section III presents the problem context. Section IV describes the AccessAI conceptual design. Section V outlines the evaluation methodology. Section VI discusses implications and limitations, and Section VII presents the conclusion and future work.

## II. RELATED WORK

This section reviews the state of the art across three areas relevant to AccessAI and identifies the knowledge gap that the proposed research aims to fill.

### A. Automated Accessibility Evaluation Tools

Automated accessibility evaluation tools have been widely adopted to support compliance checking at scale. Tools such as axe-core [4], WAVE [5], Google Lighthouse [6], and pa11y [10] perform rule-based analysis of web content against WCAG success criteria. Axe-core, developed by Deque Systems, is an open-source engine that evaluates Document Object Model (DOM) elements against a configurable rule set and integrates with Continuous Integration/Continuous Deployment (CI/CD) pipelines. WAVE provides a browser-based overlay that visually highlights accessibility issues. Pa11y provides a command-line interface for automated testing.

Despite their widespread use, these tools have well-documented limitations. Frazao and Duarte [7] found that automated tools can typically detect only 30–50% of WCAG 2.2 success criteria automatically. Vigo et al. [11] conducted a comparative study of six automated evaluation tools and observed significant variance in the issues reported. Abou-Zahra [3] emphasized that automated tools are best used alongside manual evaluation. Paterno and Schiavone [12] noted that the lack of prioritization in tool outputs makes it difficult for developers to allocate remediation effort effectively.

### B. AI and Machine Learning in Accessibility

Recent research has explored the application of AI to accessibility tasks. Gleason et al. [13] developed automated methods for generating image alt-text using computer vision models. Zhang et al. [14] applied deep learning to detect accessibility barriers in mobile application interfaces. Prakash et al. [15] investigated the use of natural language processing to assess the readability and cognitive accessibility of web content. Chiou et al. [16] explored automated captioning for video content.

The emergence of Large Language Models (LLMs) has opened new possibilities. Fan et al. [17] conducted a systematic review of LLMs for software engineering and found promising but uneven results for accessibility-related code generation. Peng et al. [18] demonstrated that AI-assisted coding tools can significantly improve developer productivity. However, the integration of LLMs into interactive, developer-facing accessibility workflows remains largely unexplored.

### C. Developer-Facing Accessibility Support

Research in HCI has identified persistent barriers to developer engagement with accessibility. Bi et al. [8] found that developers often lack sufficient knowledge of WCAG criteria and find automated tool outputs difficult to act upon. Alshayban et al. [9] analyzed accessibility issues in over 1,000 Android applications and concluded that many violations persist due to inadequate developer support rather than technical infeasibility. Moreno et al. [19] proposed method-level accessibility guidelines but found developers needed additional interactive support.

Conversational interfaces have been proposed as a mechanism for improving developer guidance. Research on chatbot-assisted development [18] suggests that natural language interaction can reduce cognitive overhead. Retrieval-Augmented Generation (RAG) [20] has emerged as a technique for grounding LLM responses in domain-specific knowledge bases. Applying conversational AI with RAG to accessibility support represents a gap that AccessAI seeks to address.

### D. Identified Knowledge Gap

No existing solution integrates automated evaluation, visualization, and conversational AI into a unified accessibility support framework. Automated engines operate in isolation without interactive remediation support [7][11]; visualization of compliance status is rare and typically limited to simple issue lists [12]; conversational AI has not yet been

applied to provide contextual, iterative accessibility guidance within development workflows [17][18].

AccessAI is designed to fill this gap. Table I summarizes these differences.

TABLE I. COMPARISON OF ACCESSIBILITY SUPPORT APPROACHES.

Feature	Manual Audit	Auto Tools	AI-Only	AccessAI
Scalability	Low	High	Medium	High
Contextual Guidance	High	Low	Medium	High
Iterative Support	Low	Low	Low	High
Visualization	N/A	Limited	N/A	Integrated
Conversational AI	N/A	N/A	Partial	Integrated
Continuous Validation	Low	Medium	Low	High

## III. PROBLEM CONTEXT AND RESEARCH GAP

Current accessibility practices generally fall into two categories: expert-led manual audits and rule-based automated testing tools [3]. Manual audits provide contextual depth and accuracy but are resource-intensive. Automated tools offer scalability but lack interpretability [7][11].

From a Smart Accessibility perspective, accessibility support systems should be adaptive, explanatory, and capable of supporting continuous improvement [1]. Developers frequently require clarification, follow-up guidance, and confirmation that applied fixes have resolved the original issue. Traditional tools rarely support this iterative and conversational workflow.

The two primary challenges addressed by this research were identified through: (1) the literature reviewed in Section II, which documents the limitations of automated tools [7][11] and developer difficulties [8][9]; (2) analysis of existing tool outputs, which revealed a consistent pattern of static, non-interactive reporting; and (3) preliminary discussions with five web developers who reported that understanding why an issue matters and how to fix it are their primary pain points. The resulting challenges are: (1) limited guidance and contextual support in existing tools, and (2) insufficient support for iterative remediation and continuous validation.

## IV. ACCESSAI CONCEPTUAL DESIGN

Accessibility refers to a wide range of potential exclusion causes, including visual, auditory, motor, and cognitive impairments [2]. AccessAI focuses primarily on the Perceivable and Operable principles of WCAG 2.2 at conformance Levels A, AA and AAA. Specifically, AccessAI targets: alternative text for non-text content (SC 1.1.1), color contrast (SC 1.4.3, 1.4.6), keyboard accessibility (SC 2.1.1, 2.1.2), focus management (SC 2.4.3, 2.4.7), form labeling (SC 1.3.1), heading structure (SC 1.3.1), and link purpose (SC 2.4.4). The Understandable and Robust principles are addressed to a lesser extent.

AccessAI is intended to be integrated at two stages: (1) during active development, operating alongside the code editor and browser developer tools for real-time feedback; and (2) during continuous integration, running as an automated check within CI/CD pipelines on each code commit [21].

The architecture consists of four integrated components: (1) automated accessibility evaluation, (2) dashboarding and visualization, (3) conversational chatbot assistance, and (4) iterative retesting. Figure 1 illustrates the system architecture.

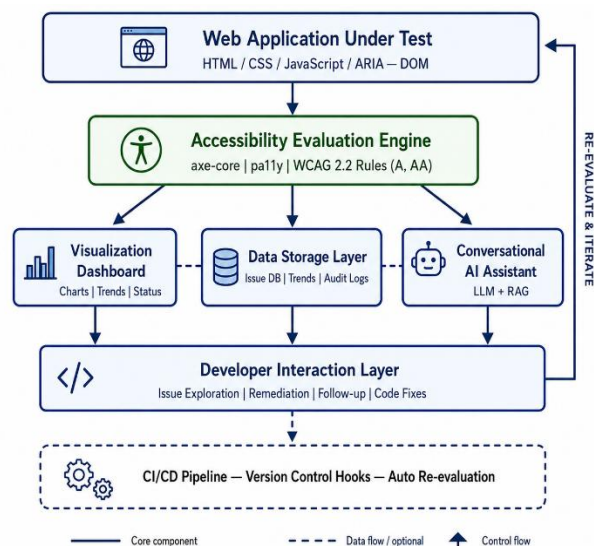


Figure 1. AccessAI system architecture.

### A. Automated Accessibility Evaluation Engine

The system builds on established automated accessibility evaluation tools as its core analysis layer. These tools programmatically assess web content against defined accessibility standards and generate structured results describing identified issues, their severity, affected elements, and references to relevant guidelines. An example of such a tool is axe-core, which provides a widely used programmatic interface for running accessibility checks.

TABLE II. EXAMPLE AXE-CORE EVALUATION OUTPUT.

Rule ID	Impact	WCAG SC	Element	Description
image-alt	Critical	1.1.1	img.hero	Image missing alt text
color-contrast	Serious	1.4.3	p.intro	Ratio 2.8:1 < 4.5:1
label	Serious	1.3.1	input#email	Form input lacks label
heading-order	Moderate	1.3.1	h4.sect	Heading level skipped

The engine assesses structural semantics, keyboard accessibility, color contrast ratios (WCAG thresholds of 4.5:1 for normal text and 3:1 for large text), alternative text for images and media, and form labeling and Accessible Rich Internet Applications (ARIA) attribute correctness. This structured output feeds into both the dashboard and conversational assistant.

### B. Dashboarding and Visualization Interfaces

AccessAI proposes interactive dashboards to visualize accessibility findings, drawing on information visualization principles [22]. The dashboard provides three views: (1) a compliance summary with proportional breakdown by impact level; (2) a trend chart displaying issue counts over successive evaluation runs; and (3) a detail view listing individual violations with remediation status and direct links to the conversational AI assistant. Figure 2 illustrates the proposed dashboard layout.

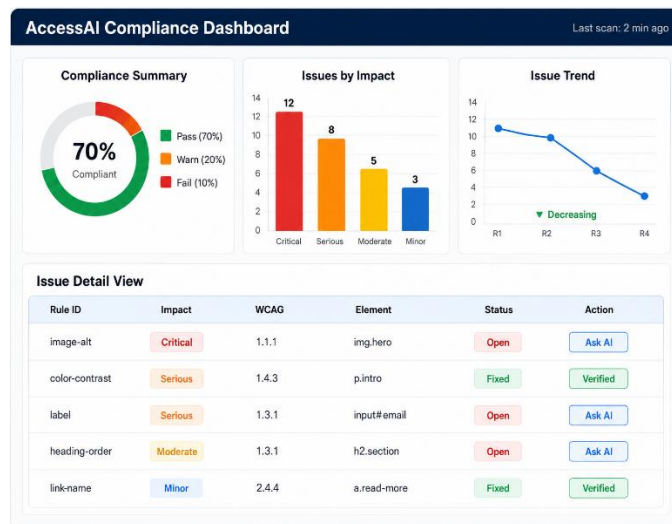


Figure 2. Proposed AccessAI dashboard layout.

### C. Conversational Chatbot Assistance

A distinguishing aspect of AccessAI is the integration of a conversational AI assistant powered by an LLM with Retrieval-Augmented Generation (RAG) [20]. The chatbot supports three interaction patterns.

First, issue explanation: when a developer selects a violation from the dashboard, the chatbot provides a natural language explanation referencing the relevant WCAG success criterion. For example, for a color-contrast violation (SC 1.4.3) with a measured ratio of 2.8:1, the chatbot explains the 4.5:1 threshold and describes the impact on users with low vision.

Second, remediation guidance: the chatbot provides context-specific remediation advice with code snippets. For the contrast example, it suggests specific Cascading Style Sheets (CSS) changes to meet the 4.5:1 threshold.

Third, follow-up interaction: developers can ask clarifying questions, request alternative approaches, or inquire about related criteria. Figure 3 illustrates the workflow with a concrete example.

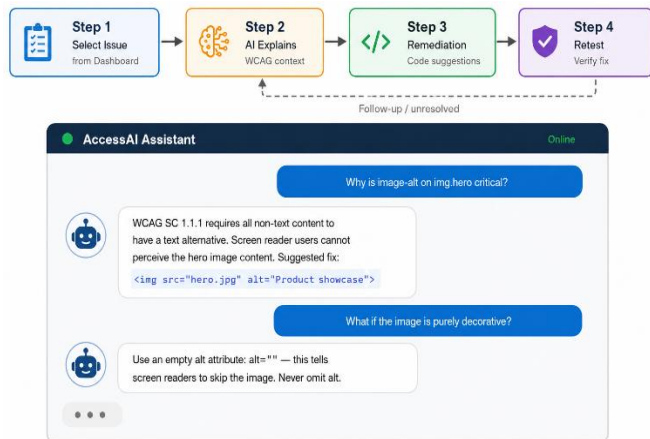


Figure 3. Conversational AI interaction workflow with example.

The RAG architecture grounds the LLM’s responses in a knowledge base containing WCAG 2.2 documentation, W3C Web Accessibility Initiative (WAI) techniques, and the specific evaluation results from the current audit. This mitigates hallucination risk compared to unconstrained generation [20].

**D. Iterative Retesting and Continuous Validation**

After a developer applies a fix, the evaluation engine is re-invoked to verify resolution. The dashboard updates to reflect the new compliance status, and the chatbot confirms the fix or identifies remaining issues. This feedback loop aligns with agile and CI/CD workflows [21], supporting accessibility as an ongoing process. The retesting mechanism integrates with version control hooks for automated checks on each commit.

**V. EVALUATION METHODOLOGY**

The evaluation follows a three-phase mixed-method approach. Figure 4 illustrates the methodology and timeline.

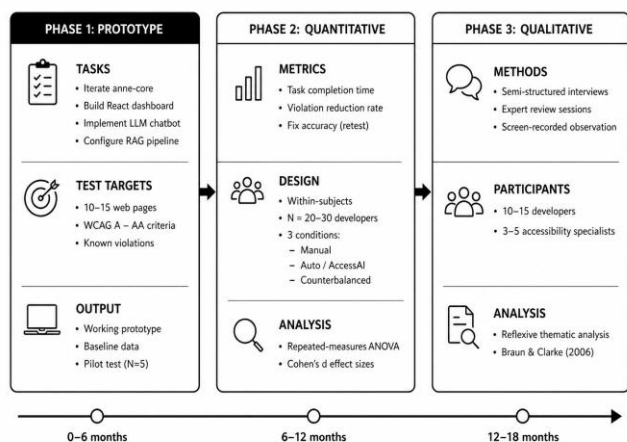


Figure 4. Three-phase evaluation methodology.

**A. Phase 1: Prototype Development**

A functional prototype will be developed that integrates three main components: (1) an automated evaluation engine

accessed via a programmatic API; (2) an interactive web-based dashboard for visualizing results; and (3) an AI-powered assistant supported by a retrieval pipeline over a structured knowledge base of relevant standards and best practices. The system will be delivered in multiple forms, including a browser-based tool and a standalone web application.

The prototype will be evaluated on a set of web pages with pre-identified accessibility issues spanning different levels of conformance. These will include both controlled test pages with known violations and real-world examples drawn from publicly available accessibility datasets.

**B. Phase 2: Quantitative Evaluation**

A within-subjects experimental design with 20–30 participants (developers with varying accessibility experience) will compare three conditions using counterbalanced task assignment: (1) manual audit using only WCAG documentation and browser developer tools; (2) automated tools using axe-core with its default report output; and (3) AccessAI using the full prototype with dashboard and chatbot.

Three metrics will be measured: (1) task completion time, defined as the time taken to identify and remediate accessibility violations; (2) violation reduction rate, defined as the percentage reduction in violations after one remediation cycle; and (3) fix accuracy, defined as the percentage of remediation attempts that pass automated retesting. Statistical analysis will use repeated-measures ANOVA with post-hoc pairwise comparisons and Cohen’s d effect sizes.

**C. Phase 3: Qualitative Evaluation**

Qualitative data will be collected through: (1) semi-structured interviews with 10–15 developers; (2) expert review sessions with 3–5 accessibility specialists; and (3) screen-recorded observation of participant interactions. Analysis will follow reflexive thematic analysis [23]. Table III summarizes the evaluation design.

TABLE III. EVALUATION METRICS AND DATA COLLECTION.

Phase	Metric	Method	Participants
Quant.	Task completion time	Timed tasks, 3 conditions	20–30 developers
Quant.	Violation reduction	Successive eval cycles	20–30 developers
Quant.	Fix accuracy	Retest pass rate	20–30 developers
Qual.	Perceived usefulness	Semi-structured interviews	10–15 developers
Qual.	Guidance quality	Expert review sessions	3–5 specialists
Qual.	Interaction patterns	Observation + thematic analysis	10–15 developers

TABLE IV. HYPOTHESIZED OUTCOMES BY CONDITION.

#	Metric	Manual	Auto Only	AccessAI
H1	Completion time	Longest	Moderate	Shortest
H2	Violation reduction	Moderate	Low	Highest
H3	Fix accuracy	High	Low–Med	High
H4	Developer confidence	Low	Low–Med	High

## VI. DISCUSSION

As an early-stage conceptual framework, AccessAI presents design direction and research intent rather than finalized empirical findings. The central premise that combining automation, visualization, and conversational AI can reduce both technical and cognitive barriers to accessibility compliance is supported by prior work on developer challenges [8][9] and conversational code assistance [18].

Compared with existing solutions, AccessAI's contribution lies in integrating capabilities that currently exist only in isolation. Automated tools excel at scalable detection but do not support remediation [4][7]. AI-based approaches show promise for remediation but lack systematic detection [17]. AccessAI combines these strengths while adding visualization and iterative retesting.

### A. Limitations and Constraints

Several limitations must be acknowledged. First, LLM-based guidance may produce inaccurate remediation advice (hallucination), particularly for complex ARIA patterns. The RAG approach [20] mitigates but does not eliminate this risk. Second, automated evaluation covers only a subset of WCAG success criteria [7]; AccessAI does not replace manual auditing for criteria requiring human judgment. Third, effectiveness may vary with developer experience level. Fourth, the current scope excludes mobile-native accessibility testing. Fifth, reliance on specific LLM providers introduces dependency and cost considerations.

### B. Ethical Considerations

AI-driven accessibility guidance raises ethical concerns regarding trust and responsible use. Developers may over-rely on AI-generated remediation without critical evaluation. The system must communicate confidence levels and encourage verification. Accessibility compliance has legal implications [24], and AI-generated guidance must not substitute for expert review.

### C. Challenges and Risks

Several challenges are anticipated: (1) RAG knowledge base currency. WCAG guidelines evolve, requiring ongoing corpus maintenance; (2) evaluation engine accuracy, false positives and negatives from axe-core may propagate; (3) LLM response latency, interactive chatbot performance depends on API response times; and (4) generalizability, the evaluation will use a limited set of test pages.

### D. Immediate and Mid-Term Future Plans

Immediate plans (0–6 months): Complete Phase 1 prototype development, including axe-core integration, React dashboard implementation, and LLM chatbot with RAG pipeline. Conduct preliminary pilot testing with 5 developers to refine the prototype.

Mid-term plans (6–18 months): Execute Phases 2 and 3 of the evaluation. Expand automated evaluation capabilities. Investigate integration with popular development environments (VS Code, IntelliJ). Explore multi-modal accessibility support, including voice-guided remediation. Conduct longitudinal studies in real-world development environments.

## VII. CONCLUSION AND FUTURE WORK

This paper introduced AccessAI, a conceptual Smart Accessibility-aligned framework for improving digital accessibility compliance. The framework integrates automated evaluation engines (axe-core, pal ly), visualization dashboards, and conversational chatbot support powered by Large Language Models with Retrieval-Augmented Generation. AccessAI targets the perceivable and operable WCAG 2.2 dimensions at Levels A, AA and AAA, addressing both detection and remediation phases.

The review of related work identified a knowledge gap: no existing solution integrates automated evaluation, visualization, and conversational AI into a unified, iterative accessibility support framework. AccessAI addresses this gap through a four-component architecture designed for integration at both development-time and CI/CD stages. A three-phase evaluation methodology has been defined with quantitative metrics and qualitative analysis.

Future work will focus on expanding coverage to additional WCAG criteria, enhancing chatbot explainability, integrating with mainstream development environments, and conducting longitudinal evaluations. The proposed direction highlights the potential of AI-driven accessibility support systems to make accessibility more scalable, actionable, and embedded within modern development practices.

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## Interacting Effects of Command Set Size and Temporal Parameters in Brain-Computer Interface Based on the RSVP Paradigm

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**Abstract**—Rapid Serial Visual Presentation (RSVP) is a promising paradigm for gaze-independent Event-Related Potential (ERP) Brain-Computer Interfaces (BCIs), particularly in accessibility-oriented applications, although performance strongly depends on interface configuration and stimulation parameters. This study examines the combined effects of command set size, Stimulus Onset Asynchrony (SOA), and number of stimulation sequences on system performance and task execution. Fourteen participants took part in an offline RSVP-based ERP-BCI experiment evaluating six interface configurations. Conditions are denoted as  $Cn-s-q$ , where  $n$  indicates the number of available commands,  $s$  the SOA in milliseconds, and  $q$  the number of stimulation sequences (i.e., repetitions of the full stimulus set). Specifically, the 6 conditions tested were denoted as C2-188-32, C4-188-16, C8-188-08, C2-375-16, C4-375-08, and C8-375-04. The total selection time was kept constant at 12 s. Performance was assessed using classification accuracy and pictograms per minute, and complemented by subjective ratings reflecting how easily participants were able to perform the target-counting task required to operate the interface. The results reveal clear trade-offs between temporal parameters and command set size, with configurations C2-375-16 and C4-188-16 achieving the highest overall performance. Moreover, conditions with longer SOAs were consistently associated with easier execution of the counting task, independently of the number of commands. These findings support conservative RSVP-based ERP-BCI designs in which command set size and temporal configuration are jointly tuned to achieve reliable control while maintaining feasible task execution.

**Keywords**-Brain-Computer Interface (BCI); Event-Related Potential (ERP); Rapid Serial Visual Presentation (RSVP).

### I. INTRODUCTION

Brain-Computer Interfaces (BCIs) have emerged as a promising assistive technology by enabling direct communication and control pathways between neural activity and external devices without relying on muscular output [1]. This capability is particularly relevant in accessibility-oriented contexts, where BCIs can provide alternative interaction channels for individuals with severe motor impairments.

Among the different BCI approaches, systems based on Event-Related Potentials (ERPs), especially those exploiting the P300 component, have been widely investigated due to their non-invasive nature, robustness, and relatively short training requirements [2].

Traditional ERP-BCIs have commonly relied on matrix-based visual paradigms, such as the classical row-column speller [3]. However, these paradigms impose substantial visual and oculomotor demands, which may limit their usability for users with gaze control deficits [4]. In response to these limitations, the Rapid Serial Visual Presentation (RSVP) paradigm has been proposed as an alternative visual stimulation approach. In RSVP-based BCIs, stimuli are presented sequentially at a single spatial location, thereby reducing the need for eye movements and minimizing spatial attention requirements [5]. These characteristics make RSVP particularly suitable for accessibility-oriented applications, where robustness across heterogeneous user capabilities is a critical design goal.

Despite these advantages, the performance of RSVP-based ERP-BCIs is strongly influenced by the configuration of the user interface and stimulation parameters. Previous studies have shown that factors such as stimulus presentation rate, the Stimulus Onset Asynchrony (SOA, i.e., the time interval between the onset of two consecutive stimuli), the number of repetitions or stimulation sequences per target, and target probability substantially affect ERP amplitude, classification accuracy, and overall system efficiency [5]–[8].

RSVP-based studies have shown that excessively fast presentation rates can degrade ERP separability, whereas slower rates reduce interaction efficiency [9]. Increasing the number of stimulation sequences (i.e., number of repetition of each stimulus) can improve classification accuracy at the cost of longer selection times [7][8].

Another key design dimension in accessible BCI systems

is the number of available commands. While expanding the command set increases system expressiveness and functional flexibility, it also reduces target probability and may negatively impact ERP detectability and overall performance [10]. At the same time, given the well-established inverse relationship between target probability and ERP amplitude [6], an excessively small command set combined with very rapid stimulus presentation may also be suboptimal, as it can alter the temporal dynamics of target detection and reduce system efficiency due to temporal overlap and refractory effects [9]. Therefore, understanding the trade-offs between command set size, temporal parameters, and interaction time is essential for designing interfaces that can be adapted to individual user needs and capabilities.

From an accessibility perspective, it is important to acknowledge that BCI performance in real end-user populations remains limited. In particular, achieving reliable and sustained BCI control continues to be a major challenge in users in a Complete Locked-In State (CLIS), who represent one of the primary target populations for assistive BCI technologies [11], [12]. These limitations highlight the gap that still exists between laboratory-based demonstrations with healthy participants and practical, everyday use in severely impaired users. Consequently, a conservative and user-centered design approach is warranted. Rather than prioritizing high expressiveness or large command sets, interface designs should focus on simplicity, robustness, and cognitive manageability. In this context, interfaces relying on a small number of commands—even as few as two—may represent a pragmatic and meaningful starting point, particularly when the goal is to ensure reliable interaction under demanding attentional and physiological constraints.

In this work, we present an experimental study that systematically evaluates different RSVP-based ERP-BCI interface configurations by jointly varying three core parameters: the number of available commands, the SOA, and the number of stimulation sequences used for decision making. By analyzing objective performance metrics together with subjective ratings of task execution difficulty during the target counting task, this study aims to provide empirical evidence to support informed, accessibility-oriented interface design choices.

## II. METHODS

### A. Participants

Fourteen French-speaking students (mean age  $21.00 \pm 1.11$  years; 7 females and 7 males) with normal or corrected-to-normal vision participated in the study. All participants were of legal age and reported no prior experience with BCI systems. Self-reports confirmed the absence of neurological or psychiatric conditions, and none of the participants were taking regular medication at the time of the experiment. Written informed consent was obtained from all participants prior to data collection.

### B. Data Acquisition and Signal Processing

EEG data were recorded at a sampling rate of 256 Hz using eight electrode positions (Fz, Cz, Pz, Oz, P3, P4, PO7, and PO8) according to the international 10–10 system. All channels were referenced to the right earlobe and grounded at FPz. Signals were amplified using a 16-channel g.USBamp amplifier (g.tec Medical Engineering GmbH, Austria) and band-pass filtered between 0.1 and 60 Hz.

Data acquisition and stimulus presentation were implemented using BCI2000 (version 3.6, R5711.1) [13]. Offline artifact correction was performed using the artifact subspace reconstruction (ASR) algorithm with default EEGLAB (version 2025.0.0) parameters [14], combined with a Riemannian distance-based approach [15]. Feature extraction and classification were carried out using the *P300Classifier* tool in BCI2000, employing Stepwise Linear Discriminant Analysis (SWLDA). Classification performance was evaluated using a 16-fold cross-validation procedure to ensure generalizability.

### C. Experimental Conditions

Six experimental conditions were defined by systematically varying three interface parameters: the number of available commands, the SOA, and the number of stimulation sequences (Table I). The number of commands was set to 2, 4, or 8 pictograms, and the SOA was set to either 187.5 ms or 375 ms. The stimulus duration was fixed at 100 ms across all conditions; therefore, variations in SOA were implemented by modifying the Inter-Stimulus Interval (ISI, i.e., is the temporal interval between the offset of one stimulus to the onset of another). These parameters resulted in different Target-to-Target Intervals (TTIs) across conditions. TTI denotes the mean time between successive presentations of the target stimulus. The number of stimulation sequences was adjusted across conditions such that it decreased as the number of commands increased. This design ensured that the total selection time per trial was constant (12 s) for all conditions, allowing direct comparisons of performance and perceived task execution across interface configurations.

The pictograms used in this study were obtained from the ARASAAC database [16] and were selected for their relevance in Augmentative and Alternative Communication (AAC) contexts (Figure 1). Stimuli were presented sequentially at the center of the computer screen, using a single fixed spatial location. Each pictogram was displayed with a diameter of 10.5 cm. The viewing distance between the participant and the display was approximately 60 cm.

### D. Procedure

The experiment was conducted in a single session using a within-subject (repeated-measures) design. Upon arrival, participants received standardized instructions, provided informed consent, and were prepared for EEG recording. No online feedback was provided during the experiment, and participants did not interact with the system in real time.

TABLE I. EXPERIMENTAL CONDITIONS USED IN THE RSVP-BASED ERP-BCI STUDY.

Condition	Number of stimuli	Stimulus onset asynchrony (ms)	Target-to-target interval (ms)	Sequences
C2-188-32	2	187.5	375	32
C2-375-16	2	375	750	16
C4-188-16	4	187.5	750	16
C4-375-08	4	375	1500	8
C8-188-08	8	187.5	1500	8
C8-375-04	8	375	3000	4

Note: Target-to-target interval values correspond to mean intervals, as the presentation order of stimuli within each sequence was randomized, resulting in local variability in the temporal spacing between successive target occurrences.

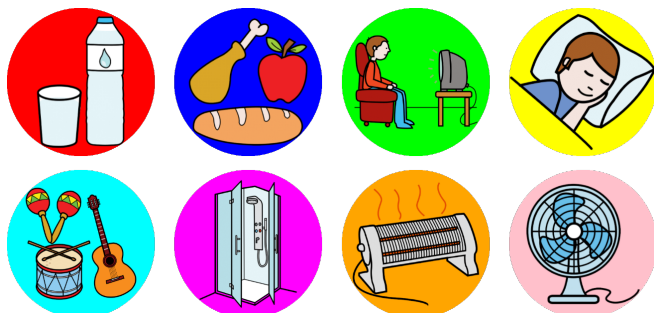


Figure 1. Pictograms used as visual stimuli in the RSVP-based ERP-BCI.

Each trial consisted of attending to a target pictogram while ignoring non-target stimuli. Participants were instructed to mentally count the number of times the target pictogram appeared in order to maintain attentional focus. A trial was defined as the selection of one pictogram from the available set, whereas a sequence consisted of a complete presentation of all pictograms in the set; therefore, each sequence included one presentation of the target stimulus. The order of pictograms within each sequence was randomized without replacement.

Each trial comprised a fixed number of stimulation sequences depending on the experimental condition, resulting in a constant trial duration of 12 s across all conditions. A 3000 ms pause preceded and followed each trial. A run consisted of eight consecutive trials (T1-T8), and each experimental condition included two runs (R1 and R2, 16 trials per condition). Before each condition, a short training run (R0) consisting of two trials was administered to familiarize participants with the stimulus presentation and timing of that configuration. These training trials used exactly the same temporal parameters as the experimental trials but were not included in the computation of classifier parameters or performance metrics. The order of conditions was counter-balanced across participants to minimize learning effects and fatigue (Figure 2 shows the experimental procedure for the particular case of the condition C2-375-16).

### E. Evaluation and Statistical Analysis

Objective BCI performance was quantified using classification accuracy (%), defined as the proportion of correctly

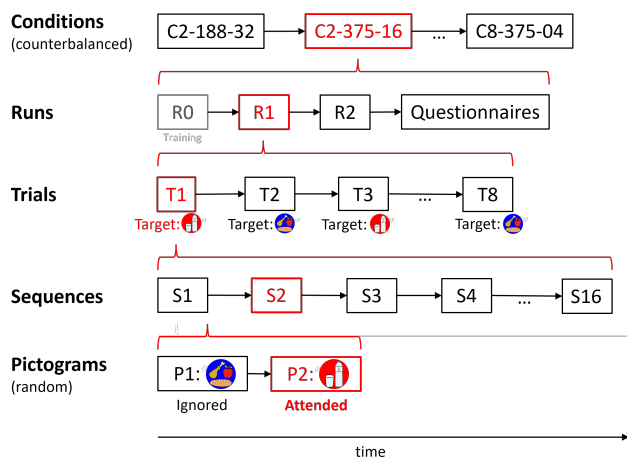


Figure 2. Experimental procedure followed by the participants.

classified target selections. Accuracy values were computed at fixed temporal intervals of 375 ms throughout the trial. This interval corresponds to the sequence duration of the fastest condition and represents the greatest common divisor of the sequence durations across all experimental configurations, thereby allowing accuracy to be tracked at equivalent temporal points across conditions. For example, the duration of a single sequence was 375 ms for C2-188-32, 1500 ms for C4-375-08, and 3000 ms for C8-375-04. However, given the number of experimental conditions and the large number of time points obtained per trial, performing a full inferential statistical analysis on the time-resolved accuracy curves would have resulted in an excessive number of multiple comparisons. For this reason, accuracy time courses were not subjected to inferential statistical testing. Instead, overall system efficiency was summarized using Pictograms Per Minute (PPM), a metric that jointly captures classification accuracy and selection speed.

PPM values were computed at each temporal update throughout the trial for every participant and experimental condition. For each participant and condition, the maximum PPM achieved over the course of the trial was then extracted and used as a summary performance measure. This procedure yields a single, representative efficiency value per participant and condition, reflecting the best achievable trade-

off between speed and accuracy under each interface configuration, and enabling direct statistical comparisons across conditions. The selection time, denoted as  $T$ , was defined as the total duration required to complete a trial, including stimulus presentation and inter-trial pauses. Specifically,  $T$  was computed as the product of the SOA, the number of stimuli per sequence, and the number of sequences, plus a 3 s pause preceding the trial and a 3 s pause following the trial. For each participant and condition, the maximum PPM achieved during the trial was computed according to (1). This approach provides a compact and interpretable performance metric while avoiding the methodological and statistical issues associated with multiple time-resolved comparisons. Although maximum PPM provides a compact summary of performance, it reflects peak performance rather than typical performance across the full trial. Therefore, it should be interpreted as an estimate of best achievable efficiency rather than sustained performance.

$$PPM = \begin{cases} \frac{(2P-1)}{T} & P > 0.5 \\ 0 & P \leq 0.5 \end{cases} \quad (1)$$

In addition, a subjective preference rating was collected at the end of each condition using a three-point Likert scale. Participants were asked to provide a single overall rating reflecting how the task was experienced, specifically how fluently they were able to attend to and mentally count the target pictogram throughout the trial. A rating of 1 indicated a frustrating and unpleasant task execution, characterized by difficulties in maintaining the count; a rating of 2 indicated a satisfactory execution despite occasional difficulties or frustration; and a rating of 3 indicated a smooth task execution, with no perceived difficulty or frustration while counting the target stimuli.

Non-parametric Friedman tests were applied for overall comparisons across conditions, followed by Wilcoxon signed-rank tests for pairwise comparisons. Effect sizes were reported using Kendall's  $W$  for Friedman tests and  $r$  for Wilcoxon tests. To control for multiple comparisons, the Benjamini–Hochberg procedure was applied to maintain the false discovery rate [17].

### III. RESULTS AND DISCUSSION

This section reports and discusses the results obtained across experimental conditions. The analysis jointly considers objective performance metrics and subjective evaluations in order to examine how variations in the number of commands, SOA, and number of stimulation sequences influence both system efficiency and perceived task execution in the RSVP-based ERP-BCI.

#### A. Performance

The classification accuracy over time for each condition is shown in Figure 3. Classification accuracy evaluated at the end of each trial—after completion of all stimulation

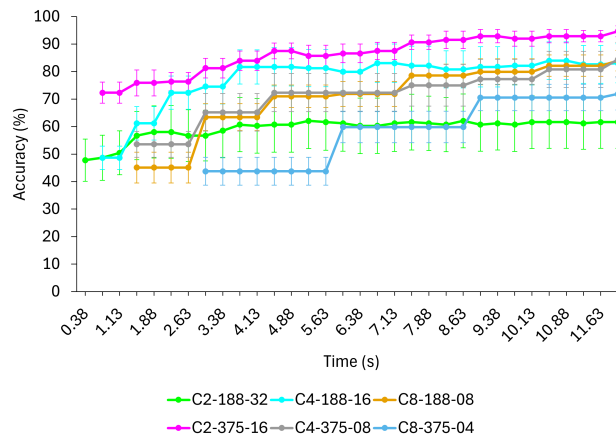


Figure 3. Classification accuracy (% , mean  $\pm$  standard error) as a function of elapsed time for each experimental condition in the RSVP-based ERP-BCI.

sequences and a fixed selection time of 12 s—varied substantially across interface configurations. Under this final-trial criterion, mean accuracies ranged from 61.61% for C2-188-32 to 94.64% for C2-375-16, with intermediate values observed for C4-188-16 (83.04%), C8-188-08 (83.94%), C4-375-08 (84.38%), and C8-375-04 (71.88%). These results indicate that the tested interface configurations did not perform equivalently in enabling reliable identification of the user's intended pictogram.

To capture overall interaction efficiency, performance was further quantified using the maximum PPM, which integrates speed and classification accuracy. A significant effect of interface configuration on maximum PPM was observed ( $p < 0.001$ , Kendall's  $W = 0.409$ ), indicating a moderate-to-strong effect size. As shown in Figure 4, condition C2-375-16 yielded significantly higher maximum PPM values than configurations combining larger command sets and/or shorter SOAs, including C4-375-08 ( $p = 0.009$ ,  $r = 0.480$ ), C8-188-08 ( $p = 0.005$ ,  $r = 0.639$ ), and C8-375-04 ( $p = 0.008$ ,  $r = 0.765$ ). Similarly, C4-188-16 outperformed both eight-command configurations, namely C8-188-08 ( $p = 0.044$ ,  $r = 0.343$ ) and C8-375-04 ( $p = 0.010$ ,  $r = 0.587$ ). Among the eight-command conditions, C8-375-04 showed significantly lower performance than both C4-375-08 ( $p = 0.019$ ,  $r = 0.417$ ) and C8-188-08 ( $p = 0.010$ ,  $r = 0.430$ ).

Taken together, accuracy evolution and maximum PPM results do not point to a single parameter as the dominant determinant of performance. Instead, performance emerges from a trade-off between command set size, temporal configuration, and number of stimulation sequences. Notably, the two best-performing conditions (C4-188-16 and C2-375-16) differ markedly in both SOA and number of commands, yet share a similar TTI of approximately 750 ms. Conditions with intermediate TTIs (C4-375-08 and C8-188-

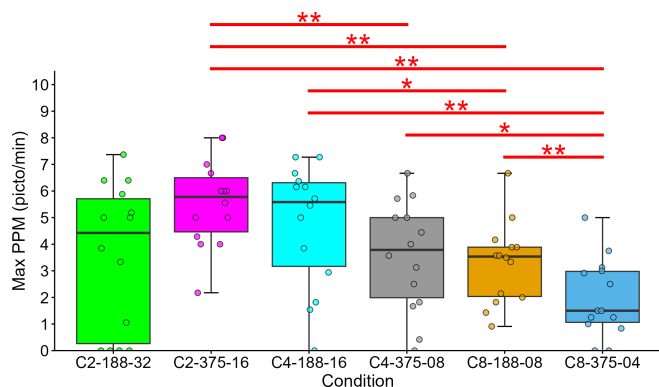


Figure 4. Distribution of the maximum pictograms per minute (PPM) across experimental conditions in the RSVP-based ERP-BCI. Red lines indicate statistically significant pairwise differences (\*  $p < 0.05$ , \*\*  $p < 0.01$ ).

08, around 1500 ms) yielded intermediate performance. In contrast, configurations with extreme TTIs were associated with less stable outcomes. In particular, although C2-188-32 did not yield the lowest median performance, it showed the highest inter-individual variability, with several participants achieving zero maximum PPM values, indicating unreliable control under excessively rapid stimulation (TTI  $\approx 375$  ms). Similarly, overly slow stimulation combined with a small number of sequences (C8-375-04, TTI  $\approx 3000$  ms) resulted in reduced overall performance.

Importantly, as indicated, C2-188-32 included cases in which maximum PPM values were equal to zero. In these cases, the classifier could not be reliably computed by the *P300Classifier* tool, suggesting that the combination of very short TTI and high stimulation rate may exceed both user attentional capacity and the robustness of the classification approach. While this effect may partly reflect user-related difficulties in task execution, it also motivates future work exploring more sophisticated signal processing and classification methods for extreme temporal configurations.

Overall, these findings are consistent with previous RSVP-based BCI studies highlighting the critical role of target probability and temporal spacing in ERP detectability [5]–[7]. The present results further confirm that RSVP-BCI performance arises from the interaction between temporal and structural design choices rather than from any single parameter in isolation.

### B. Perceived Task Execution

Subjective evaluations of task execution were analyzed to complement the objective performance results. After each condition, participants rated the perceived fluency and difficulty of the counting task using a three-point scale, reflecting how easily and comfortably they were able to carry out the required attentional task. The obtained results of the subjective evaluations are shown in Figure 5.

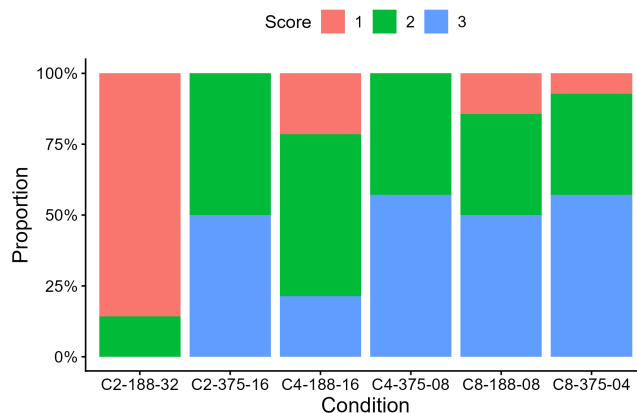


Figure 5. Percentage of users selecting each rating for perceived task execution across experimental conditions in the RSVP-based ERP-BCI (1: *frustrating and unpleasant task execution*; 2: *satisfactory task execution despite some difficulty or frustration*; 3: *smooth task execution with no frustration or perceived difficulty*).

A significant effect of experimental condition on perceived task execution was observed ( $p < 0.001$ , Kendall's  $W = 0.472$ ). Post-hoc analyses showed that condition C2-188-32 was rated significantly worse than all other configurations, including C2-375-16 ( $p = 0.006$ ,  $r = 0.845$ ), C4-188-16 ( $p = 0.021$ ,  $r = 0.641$ ), C4-375-08 ( $p = 0.006$ ,  $r = 0.854$ ), C8-188-08 ( $p = 0.007$ ,  $r = 0.727$ ), and C8-375-04 ( $p = 0.007$ ,  $r = 0.795$ ). This result indicates that the combination of a minimal command set with very rapid stimulation and a short TTI led to a significantly more difficult and frustrating task execution.

Notably, C2-188-32 was also the condition in which several participants failed to achieve adequate BCI control. In these cases, classification accuracy did not exceed chance level (50%), resulting in maximum PPM values equal to zero according to the adopted performance criterion. The co-occurrence of poor subjective ratings and unstable objective performance suggests that excessively rapid stimulation can exceed users' attentional processing capabilities, thereby compromising both task execution and system reliability, as previously noted in RSVP-based BCI paradigms [7][8].

In contrast, configurations with longer SOAs and reduced or intermediate command set sizes (e.g., C2-375-16, C4-375-08, and C8-375-04) were more frequently rated as easier to perform the target pictogram counting task. These conditions appear to support more stable task execution, even when objective performance did not reach its maximum, indicating that perceived ease of task execution does not necessarily scale linearly with accuracy or information throughput.

## IV. CONCLUSION AND FUTURE WORK

This study examined how key interface parameters shape the performance and task execution of an RSVP-based ERP-BCI, with a particular emphasis on accessibility-oriented design. By jointly manipulating command set size (2, 4 or 8),

SOA, and number of stimulation sequences while keeping total selection time constant, the results provide empirical evidence of the trade-offs governing RSVP-BCI interaction.

Among the tested configurations, C2-375-16 and C4-188-16 achieved the most favorable balance between performance and feasibility of task execution. Although these conditions differ in both command set size (2 and 4 stimuli) and SOA (375 ms and 187.5 ms), they share a comparable TTI (approximately 750 ms), suggesting that temporal spacing between successive target presentations plays a critical role in enabling reliable control.

Overall, the findings show that RSVP-BCI performance does not depend on any single parameter in isolation, but rather emerges from the interaction between structural and temporal design choices. From an accessibility perspective, this supports conservative interface designs that prioritize robustness and manageable task demands over maximal expressiveness. In addition, it is important to acknowledge the well-known gap between offline evaluation and real-time (online) BCI performance, where factors such as user adaptation, feedback, and non-stationarities may affect system reliability. Future work will explore adaptive parameter optimization and multimodal ERP-based BCIs combining visual RSVP with auditory and/or tactile stimulation, with the aim of improving robustness and usability for users with the most severe motor impairments, as well as validation in online and clinical settings.

#### ACKNOWLEDGMENTS

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