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Article

Toward an LLM-Driven Multimodal Accessibility Framework for Diverse Curatorial Contexts

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Abstract: Current research on museum accessibility has widely adopted sensory substitution technologies such as haptic feedback systems, virtual reality (VR), augmented reality (AR) and spatial audio technologies; however, most existing studies focus on a single technology and lack a unified framework capable of coordinating different assistive technologies, addressing diverse disability needs, and interpreting curatorial semantics. To address this research gap, this paper proposes a conceptual framework for a Curatorial Accessibility-oriented Large Language Model (CA-LLM) that integrates sensory substitution technologies. Grounded in sensory substitution theory and drawing on Research through Design (RtD) and participatory co-design methodologies, this framework constructs a three-layer system architecture comprising an input perception layer, a cognitive hub layer and a sensory output layer. It enables the intelligent coordination of curatorial knowledge, accessibility expertise and multimodal assistive technologies, thereby providing contextualised and personalised accessible curatorial experiences for people with diverse disabilities. This paper further discusses the framework's potential contributions to the theory of accessible curation and museum practice, whilst critically examining the framework's philosophical foundations, the boundaries of current AI capabilities, the practical constraints on its scalability across diverse curatorial contexts, and the ethical and cultural tensions its deployment would generate.

Keywords: accessible curation; large language models; sensory substitution; co-design; research through design; multimodal interaction

1. Introduction

According to the World Health Organization and the World Bank, approximately 15% of the world's population lives with some form of disability [1]. However, people with disabilities remain significantly underrepresented in cultural participation: individuals with disabilities comprise less than 7% of cultural attendees in exhibition spaces, while only 5.5% of people with visual impairments reportedly visit museums in Europe [2,3]. Although these figures are not directly methodologically comparable, they reveal a persistent gap between the proportion of disabled people in the general population and their representation among museum visitors [4]. Existing provision also remains limited. A joint survey by VocalEyes and the Museums Association found that although 64% of venues had implemented basic physical accessibility measures, only 6% offered audio-described guides and 11% offered handling or tactile objects [5]. Moreover, Poria et al. found that even where museums had implemented accessibility measures, visitors with physical and visual impairments could still report highly negative visit experiences [6].

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This paper's use of the term "disability" is grounded in the social model articulated by the Union of the Physically Impaired Against Segregation, which held that "it is society which disables physically impaired people" through unnecessary isolation and exclusion from full participation [7], and later systematized by Oliver [8] as a materialist theory locating the source of disability not in individual impairment but in the disabling structures of the built and social environment. Accordingly, the sensory-substitution technologies discussed in this paper are conceived not as remedies for individual deficit, but as interventions into the disabling design of curatorial environments themselves.

In contemporary curatorial practice, this paper argues that the causes of the aforementioned problems are essentially twofold. Firstly, scholars have variously critiqued museum accessibility as amounting to "tacked-on" provisions retrofitted after the fact, as premised on an unexamined "ableist assumption" that sight is the primary channel through which culture should be experienced [9]. Kleege extends this critique by arguing that, who argues that the vast majority of accessibility provisions designed for visually impaired visitors in today's museums, such as Braille and audio guides, are, in essence, conceived in the abstract by sighted people sitting in offices, intended to serve sighted aesthetic sensibilities or to satisfy compliance review, and remain entirely detached from the actual cognitive realities of people with disabilities [10]. The core objective of curatorial accessibility design is oriented toward passing compliance review rather than toward investigating the subjective, qualitative pain points and lived viewing experiences of disabled visitors [11]. The second structural barrier concerns the resources and expertise required to develop and maintain effective accessibility provision. Surveys of museums and galleries consistently identify financial constraints, limited staff expertise, and insufficient accessibility training as major barriers to improving provision [12,13]. These institutional constraints are particularly significant for smaller organisations, where accessibility expertise may not be available in-house.

In response to these problems, this paper proposes an LLM-driven multimodal accessibility system. Rather than reporting on an already-completed system implementation, this paper draws on a critical literature review of existing key technologies to propose a conceptual framework for an intelligent accessibility support system. The proposed system takes a curatorial domain large language model as its cognitive hub, co-created through the active participation of people with disabilities, and integrates multimodal perception technologies. This framework is intended to serve as a professional support tool for curators and exhibition organizers, enabling professional-grade accessibility design to be implemented economically and efficiently across diverse curatorial contexts without requiring a permanently in-house team of experts.

2. Related Work

Existing studies have explored the application of large language models (LLMs) and related AI technologies in curatorial and cultural heritage contexts. Wang et al. developed VirtuWander, a multimodal virtual museum tour system using a pack-of-bots approach and prompt engineering, while Ye et al. introduced ICH-Qwen, a domain-specific model for intangible cultural heritage preservation based on the Qwen series [14,15]. Beyond LLMs, emerging multimodal technologies have also been investigated for enhancing museum accessibility; however, their applications remain fragmented and face various limitations. This section reviews four categories of technologies that inform the proposed accessibility-oriented curatorial LLM framework.

2.1. Tactile Perception Technologies: Haptic Feedback Gloves and Refreshable Tactile Displays

Haptic feedback gloves and refreshable tactile displays simulate tactile perception through physical stimuli, providing information that would otherwise be primarily accessed through vision. Haptic gloves can generate force feedback while supporting motion tracking and direct interaction within virtual environments [16]. Refreshable tactile displays use arrays of actuators to deliver distributed tactile information, including pressure, contact, vibration, sliding, and surface roughness [17].

The National Gallery of Prague's 2018 Touching Masterpieces project demonstrates the curatorial potential of this technology. Using haptic gloves and high-precision 3D-scanned replicas of three sculptures, Michelangelo's David, the Venus de Milo, and the bust of Nefertiti, visitors could interact with digital representations of sculptures through touch.

However, this category of haptic feedback device also suffers from numerous problems in practical application. Zhang points out that the greatest bottleneck to the wider adoption of current spatial haptic devices in museum and similar settings is the "manual authoring bottleneck", together with the high capital sunk cost of the hardware itself [18]. The paper notes that manually configuring force-feedback parameters for each individual exhibit requires an extremely high level of specialized expertise, which greatly impedes the democratization of accessible haptic technology. Vidal-Verdu and Hafez point out that unlike text that can be translated sentence by sentence, the conversion from visual images to tactile signals cannot follow the same routine [19]. When complex images are converted for tactile perception devices, it often leads to severe perceptual limitations. Furthermore, tactile signals that are not designed based on the lived tactile experiences of blind individuals may reproduce the "sighted people" accessibility trap identified by Kleege [10]. Souradi et al. note that visually impaired individuals, when using haptic feedback devices in isolation, readily fall into what is termed "the semantic chasm": they can clearly perceive that there are physical undulations on the display, but are entirely unable to determine what these represent, nor can they mentally construct the spatial and logical relationships among the different parts [20].

2.2. Virtual Accessible Exhibitions: Virtual Reality Head-Mounted Displays (VR HMDs)

VR is defined as an experience that attempts to create a sense of bodily presence in a non-physical world by surrounding the user with images, sound, or other stimuli [21]. Virtual Reality accessibility is increasingly understood not merely as enabling disabled users to operate VR systems, but as ensuring equitable, safe, and meaningful immersive experiences that accommodate diverse physical abilities and preferences [22]. For visitors with mobility impairments, VR exhibitions function as an alternative means of cultural participation by overcoming architectural barriers and enabling access to otherwise inaccessible exhibition environments [23]. In addition, existing technologies allow VR to further benefit individuals with low vision: the SeeingVR system developed by Zhao et al. optimizes the experience of low-vision users interacting with VR tools through techniques such as "Magnification Lens", "Enhancement", and "Peripheral Remapping" [24].

However, VR-based accessible exhibitions at their current stage of development are also beset by a range of problems. Using participatory workshops combined with semi-structured interviews, a research team from the Hong Kong University of Science and Technology examined the VR museum experiences of six older participants aged 60 to 70. The study found that five participants repeatedly raised questions such as "Where am I?" and "How do I get to this location?" while navigating the VR museum environment. One participant noted that, even in physical museums, visitors often need to spend considerable time examining signage before locating a desired artwork, making the process tiring and time-consuming. Moreover, four of the six participants expressed dissatisfaction with the interpretive content provided by the system, feeling that it was not designed to match older adults' level of knowledge. As one participant put it directly: the explanations were excessively specialized, and the information presented exceeded their level of knowledge, making it somewhat difficult to understand [25].

2.3. Augmented Reality (AR) Visual Assistance Systems: Augmented Reality Head-Mounted Displays (AR HMDs)

Because accessible AR remains a highly interdisciplinary and emerging field, no single, widely accepted definition has yet been established. This paper therefore adopts a working definition: Accessible AR refers to the dynamic optimisation of user interfaces (UIs), interaction channels (multimodal input and output), and three-dimensional spatial rendering to provide users with sensory, cognitive, or motor impairments with compensatory information. This enables them to perceive, manipulate, and understand the integration of virtual content and physical exhibition spaces within an AR environment with levels of efficiency and immersion comparable to those of non-disabled users. Following Azuma's description of video see-through AR HMDs, this paper adopts an approach in which external cameras capture the surrounding environment and combine it with real-time rendered virtual imagery displayed through the headset [26]. Contemporary devices such as the Apple Vision Pro and Meta Quest 3 are based on this architecture.

At the present stage, AR devices hold considerable potential for use in accessible exhibition contexts and

have already demonstrated a certain degree of effectiveness. For instance, the see-through property of AR devices allows individuals with hearing impairments to receive compensatory information through digitally enhanced content while still being able to see the real world, including people and sign language within it [27]. The broader communicative capacity afforded by AR devices' support for contactless gesture-based interaction interfaces can likewise enhance the sense of interactivity and engagement that people with disabilities experience when using accessible services [28]. When combined with sign language recognition (SLR) and sign language translation (SLT) technologies, deaf and hard-of-hearing users can also make use of accessible AR devices with relative ease [29].

However, despite these advantages, AR HMDs are also subject to hardware-level limitations. Baumeister et al., in a study comparing three AR display technologies, found that the two head-mounted devices tested, including a video-see-through AR HMD, exhibited a significant increase in user cognitive load caused by limitations in field of view, whereas the spatial, projection-based AR condition did not show this effect [30].

2.4. Audio Interpretation and Audio Navigation: AI-Based Spatial-Audio Intelligent Guidance and Navigation Systems

In contrast to the traditional, one-size-fits-all audio guide intended for general audiences, an AI-based interactive smart guide can operate through voice interaction, allowing users to ask questions in real time while the AI generates targeted responses based on semantic content and environmental context; such a system can further be optimized to address the specific needs of people with disabilities, and existing academic research on this model of accessible service has likewise reported relatively positive user feedback [31]. According to Connors et al., a cognitive map constructed from a spatial, audio-based virtual environment can be used to help visually impaired individuals explore and learn the layout of unfamiliar and complex indoor environments [32]. Technologies of this kind are of considerable importance in using audio to help people with disabilities experience accessible exhibitions.

However, Wang likewise notes in her research that the substantial workload involved in designing traditional audio navigation systems constitutes an important obstacle to their widespread deployment [31]. Connors et al. regard the steep learning curve and high barrier to entry currently associated with spatial audio navigation as the greatest problem facing this type of technology at present [32].

3. Method

3.1. Design-Oriented Research Approach

The numerous technologies introduced above can undoubtedly play a significant role in accessible curatorial practice, yet each, to varying degrees, faces a range of problems and limitations. This paper therefore proposes a comprehensive system integrating a range of contemporary accessibility technologies, grounded in sensory substitution theory [33,34]. This theory holds that disabled individuals can construct cognitive representations otherwise dependent on an absent sensory modality provided the brain can process an appropriate substitute sensory input. However, such technologies, while theoretically well-supported, have yet to achieve widespread real-world adoption. Accordingly, the system proposed here aims to compensate for the visual, auditory, and mobility-related sensory information lacking among disabled individuals through tactile perception technologies, VR HMDs, AR HMDs, and AI-based spatial-audio intelligent guidance and navigation systems. These technologies are collectively referred to below as sensory substitution technologies and use alternative sensory channels to convey information.

Accordingly, this study adopts a design-oriented conceptual methodology inspired by the Research through Design (RtD) approach. As Zimmerman et al. argue, RtD employs design practice as a means of producing new knowledge rather than simply creating new artefacts [34]. As this research aims to propose a new AI-assisted framework for accessible curation, rather than to validate an already-existing technology, it adopts a design-oriented approach that draws on RtD's emphasis on exploring research questions through the very act of design. Within this framework, this paper explores how an LLM framework for curatorial accessibility can integrate sensory substitution technologies to support accessible multimodal curatorial experiences.

3.2. Participatory Co-Design Process

To ensure that this system provides a practical tool for improving disabled visitors' exhibition experiences, disabled individuals should be involved throughout the design process. This commitment aligns with Charlton's advocacy of "nothing about us without us", which holds that decisions affecting disabled people's lives, including the design of technologies and environments intended for their use, must be made with their direct participation rather than on their behalf [35].

Accordingly, the role of disabled individuals within this system should be understood through the lens of the co-creation/co-design paradigm proposed by Sanders and Stappers: disabled participants are not merely testers who engage only at the final evaluation stage, as is conventional in traditional accessibility design [36]; rather, they function as "experience experts" who participate throughout the design process, from initial planning to implementation and evaluation, and collaboratively develop design principles with curators and other stakeholders.

Moreover, the contemporary curatorial context is shaped by complex workflows, specialised roles, and cross-disciplinary collaboration. Therefore, multi-stakeholder participation throughout the design process is essential. The participating groups form an expert panel comprising disabled visitors, curators, accessibility experts, and artists. The participatory process follows Spinuzzi's three-stage framework: initial exploration, participatory discovery, and iterative prototyping [37]. The iterative evaluation of prototypes serves as a dialectical space for co-interpretation and continuous negotiation. Through sustained cycles of reflection and iteration, this process enables the elicitation of tacit needs across different stakeholder roles and expands the system's potential value-in-use. Subsequently, participants engage in deliberation and negotiation to balance artistic creation, curatorial narratives, and accessibility and usability requirements.

3.3. Requirement Discovery

The four categories of stakeholders within the expert panel hold diverse and heterogeneous requirements for this system. As analyzed above, existing technology-implemented accessibility experiences exhibit a range of documented deficiencies, including the semantic chasm and the lack of bidirectional interactivity [19, 20, 25]. Meanwhile, accessibility curators face challenges including excessively high labor costs for content production and elevated development barriers [18]. Furthermore, artists may be concerned with issues as pertaining to the presentation format of their works and the preservation of authorial intent. These circumstances require ongoing stakeholder deliberation and negotiation throughout the design process to balance different requirements.

4. Conceptual System Framework

The proposed system is organized into a three-layer architecture comprising an Input Perception Layer, a Cognitive Hub Layer, and a Sensory Output Layer.

4.1. Input Perception Layer

This layer is responsible for collecting diverse types of information within the exhibition space, including 3D modeling data of exhibits, as well as curatorial texts and interpretive narratives. At this layer, the intervention of AI can reduce human labor and financial costs to a certain extent. For instance, Luetzenburg et al. demonstrated that the LiDAR sensor integrated into the Apple iPhone 12 Pro (Apple Inc., Cupertino, CA, USA) possesses engineering application value within a defined range, capable of constructing high-resolution three-dimensional models of small objects exceeding 10 cm in size, with an absolute error margin of approximately ±1 cm, illustrating the cost and portability advantages of consumer-grade devices for this task [38, 39]. Moreover, recent research has indicated that video footage captured by smartphone-mounted gimbals, when combined with 3D Gaussian Splatting (3DGS) technology, can yield digital scenes characterized by high visual fidelity and real-time rendering capabilities. This approach offers a more efficient workflow for museum digital twin construction and accessible spatial modelling while reducing associated costs [39]. Although an error margin of ±1 cm remains inadequate for haptic perception applications, the continued advancement of consumer-grade LiDAR devices in recent years, combined with the integration of datasets

derived from multiple techniques, may enable further reduction of error margins into a practically usable range.

4.2. Cognitive Hub Layer

This layer constitutes the core of this system: a domain-specific, accessibility-oriented curatorial LLM built upon open-source models. Because this model is applied within the curatorial domain, and contemporary curation itself constitutes a highly vertical and specialized field, particular attention must be paid to this specificity. As Marty and Jones observe, over the past several decades museums have undergone a shift from being conceived as repositories of artifacts to being conceived as repositories of knowledge [40]; museum information is therefore no longer simply text or the artifacts themselves, but a composite interwoven from multiple sources, including the physical objects in the collection, the metadata describing those objects, and the curatorial context within which those objects are situated, and it is correspondingly difficult for a general-purpose LLM, detached from such context, to interpret museum information. Furthermore, because people with different disabilities have distinct accessibility requirements, a general-purpose LLM may struggle to accommodate the full range of disability-related needs [41]. Given that large language models are susceptible to hallucination, generating fluent but factually unsupported content, this study proposes a domain-specific Curatorial Accessibility LLM designed as a knowledge-grounded system rather than a purely generative model [42,43].

To enable this model to achieve sensory transformation and sensory substitution functions, its training requires substantial volumes of domain-specific curatorial accessibility data. Specifically, artwork 3D data derived from consumer-grade LiDAR and video-based 3D Gaussian Splatting (3GS), alongside corresponding ground-truth measurements obtained from industrial-grade metrological instruments, will be fed into the model over multiple training rounds. Subsequently, disabled visitors will participate deeply in the evaluation process, assigning weighted assessments to the generated outputs. Through multiple rounds of iterative training and feedback-driven refinement, the model will progressively optimize its capacity to generate accurate, contextually appropriate, and perceptually meaningful accessibility content.

4.3. Sensory Output Layer

This layer comprises the four categories of hardware enumerated above: tactile perception technologies, VR HMDs, AR HMDs, and AI-based spatial-audio intelligent guidance and navigation systems. Beyond outputting distinct types of substitute sensory information afforded by each hardware modality, this layer additionally enables the Curatorial Accessibility LLM, drawing upon its extensive repository of accessibility design cases and domain knowledge, to generate holistic accessibility design recommendations tailored to the specific circumstances of a given exhibition, including its curatorial theme, gallery environment, and other contextual factors. In this capacity, the LLM functions not merely as an information delivery engine but also as an accessibility design assistant to curators, supporting them in achieving more effective and comprehensive accessibility outcomes throughout the exhibition design process. In the study by Ye et al., the ICH-Qwen model they designed served, to some extent, as an AI expert in the field of cultural heritage [15].

4.4. Future Validation Strategy

Guided by the RtD paradigm, the validation strategy is not intended to test hypotheses regarding an existing technology through controlled experiments, but to generate design knowledge about AI-assisted accessible curation through iterative development and multi-stakeholder participation [34]. Consistent with Gaver's call for design research to resist premature convergence toward standardized solutions, this iterative process is expected to surface divergent, context-specific findings rather than a single generalizable result [44]. Accordingly, the primary outcome of evaluation is not merely system performance, but transferable design knowledge concerning AI-mediated accessibility in curatorial practice.

Formative evaluation will involve three cycles of participatory co-design workshops. Disabled visitors will participate as design partners throughout all iterations, consistent with Druin's cooperative inquiry framework [45]. The first cycle will examine whether the system addresses the needs of disabled visitors,

curators, accessibility experts, and artists. The second cycle will assess the input-perception workflow, including comparisons between consumer-grade LiDAR and 3DGS reconstruction results and industrial-grade measurements, as well as other multimodal input functions. The third cycle will focus on sensory conversion within the cognitive hub layer and the integration of the sensory output layer. Participants with disabilities will assess whether the generated haptic, audio, and spatial content effectively supports their exhibition experiences. Each cycle will conclude with a structured debriefing, allowing stakeholders to negotiate competing requirements in accordance with Sanders and Stappers' co-design methodology [46].

Following this formative evaluation, a four-week summative pilot programme will be conducted with partner museums, involving visitors with disabilities, curators, and artists. A mixed-methods approach will combine semi-structured interviews, observational task-completion measures, system-log analysis, and standardized usability questionnaires. Evaluation will focus on two dimensions: system performance, including hallucination rate, response latency, and 3D reconstruction accuracy; and user experience, including usability, assistive-technology satisfaction, and cognitive load. Ethical approval, informed consent, data anonymization, and secure data management will be incorporated into the study design. Through this integrated validation process, the research aims to assess the technical feasibility of the proposed framework while generating actionable knowledge for AI-mediated accessibility design in cultural heritage contexts.

5. Discussion

In line with the RtD orientation of this study, this discussion focuses on the design knowledge generated through the iterative conceptual process rather than validated system performance, which requires future empirical evaluation. Based on the analysis of existing accessible curatorial technologies and their limitations, this paper proposes a curatorial accessibility-oriented LLM framework that integrates sensory substitution technologies through a knowledge-grounded, co-designed mediating layer. The framework positions the LLM not as an autonomous curatorial agent, but as a cognitive and informational intermediary that coordinates curatorial knowledge, accessibility expertise, user feedback, and multimodal assistive technologies. Its function is to support the retrieval, transformation, organisation, and allocation of curatorial information according to exhibition contexts and individual access needs. This section discusses three theoretical contributions and four limitations and challenges of the proposed framework.

5.1. Theoretical Contributions

The first design knowledge generated by this framework concerns a shift from fragmented assistive devices to an integrated accessibility ecology. Existing assistive technologies often address isolated perceptual needs, whereas exhibition experiences require coordinated access across multiple dimensions. The proposed framework therefore does not treat individual assistive technologies as independent solutions, but as interoperable components coordinated through a shared cognitive and informational layer. Accessibility is consequently reconceptualised not as the provision of a particular device for a particular impairment, but as the context-sensitive orchestration of multiple access pathways. As Ellcessor observes, accessibility is "not a single process, but a web of meanings and practices" through which particular forms of access are produced [47].

Beyond the challenge of integrating fragmented accessibility tools, the second design insight concerns a personalization bottleneck: because disabled visitors present a wide range of disability types and backgrounds, no single descriptive strategy can serve their varied needs, and traditional, mechanically applied accessibility services struggle to respond from the standpoint of disabled visitors' own needs [27].

While integration and personalization address key conceptual limitations of existing accessibility approaches, the third design insight concerns the practical challenge of implementing such a framework. Resolving the two problems above is achievable in principle, but bottlenecked in practice by the substantial specialist labor these sensory substitution technologies demand, since each functions as an intermediary layer of information transformation, requiring that raw curatorial information first be gathered and then re-encoded as haptic parameters, audio descriptions, immersive virtual exhibitions, AR visual assistance content, and navigation scripts. However, scaling such technologies remains challenging because each modality requires

specialised knowledge and substantial manual transformation of curatorial information.

These practical constraints highlight the need for a coordinating mechanism capable of reducing such complexity. In this context, we observe that context-specific semantic construction, personalized generation, and the streamlining of information acquisition and quality optimization are precisely the capabilities at which large language models excel; a curatorial accessibility-oriented LLM therefore holds considerable potential to integrate and optimize these sensory substitution technologies. Furthermore, integrating multiple sensory substitution technologies into a single system is critical because disabled visitors' access needs in exhibition spaces cannot be reduced to one-to-one mappings between impairments and technologies. Individuals with multiple co-occurring impairments often fall outside single disability categories and are overlooked by assistive technologies designed around isolated impairment types. This limitation is evident among deafblind individuals, who report that technologies developed separately for visual or hearing impairments often fail to address their needs [48]. Indeed, 51% of individuals living with three or more impairments do not consider current assistive technologies to adequately address their needs or support their daily activities [48]. A more integrated, multisensory, and personalized approach to accessibility may therefore better serve this population than a fragmented, single-modality paradigm.

Moreover, the second design knowledge concerns Co-design as Redistribution of Epistemic Authority. This reframing responds to a fundamental critique of accessibility design: that it has historically reproduced testimonial and hermeneutical injustice by granting non-disabled designers authority to define what counts as "accessible" or "meaningful", while marginalising disabled visitors' own interpretive knowledge within the design process [49,50]. Eardley et al. note that when accessibility is understood merely as a substitute for absent vision, it may nonetheless continue to perpetuate ableism and ocularcentrism [9]; accessible content should instead be co-created by blind and sighted individuals alike, and should form part of a museum's core cultural practice. Accordingly, in order for this system to enable disabled individuals to experience exhibitions on their own terms through sensory substitution technologies, co-design at the level of system design is essential. Disabled participants should not merely evaluate whether the final output is usable, but should also participate in determining which curatorial information matters most, what information should not be simplified, what information may be experienced as offensive or paternalistic, which modal transformations risk undermining a work's meaning, and what degree of assistance would undermine autonomous exploration. Given the particular nature of this project within curatorial environments, the co-design process also involves curators and artists. Co-design therefore serves not only to collect requirements but also to make design conflicts visible and negotiable. Spinuzzi characterizes participatory design as a methodology with its own methods, research designs, evaluative criteria, and limitations, rather than a generic attitude of merely "involving users" [37]. Accordingly, this study's future co-design process should document how conflicts of interest arise, which needs are prioritized, who makes the final decisions, and which disagreements remain unresolved, rather than reporting only whether participants were satisfied.

In addition, the third theoretical contribution concerns implications for curatorial practice and institutional management. First, this framework yields a shift from what Björgvinsson, Ehn, and Hillgren term "projecting", where validated accessibility content, user feedback, spatial data, and design cases accumulate as institutional knowledge that can persist and evolve beyond individual exhibitions [51]. This addresses a documented problem: many current accessibility measures are produced on an ad hoc basis around a single exhibition, such that the knowledge, scripts, and annotations involved are difficult to reuse once the exhibition has ended. The system proposed in this project, by positioning itself as a repository capable of holding disabled people's voices and curatorial experience rather than a merely mechanical tool, adjusts dynamically as practices diversify and needs evolve. Second, this system changes existing accessible-curation workflows: whereas existing accessibility design is largely appended after a curatorial project has essentially been completed, the support this project provides can intervene from the point at which exhibition themes, work selection, spatial planning, and interpretive strategy are being formed, and artists may even draw on experiences afforded by sensory substitution technologies in their own creative process, giving rise to an entirely new exhibition experience. Finally, the deployment of such a new system within curatorial environments will also bring new professional

roles and responsibilities; the system's purpose does not lie in eliminating accessibility staff or accessibility design experts, but in bringing a new dimension of experience to traditional accessibility design. This aligns with Gray and Suri's broader observation regarding automation: "the great paradox of automation is that the desire to eliminate human labor always generates new tasks for humans" [52]. Museums must therefore clearly determine who is responsible for approving AI-generated content, updating the knowledge base, auditing navigational safety, maintaining hardware, and handling data. Otherwise, the purported cost reduction may simply displace labor onto curators or precariously employed temporary staff, rendering that labor less visible rather than genuinely reducing it.

5.2. Limitations and Challenges

The first challenge facing this framework concerns the philosophical limitations of sensory substitution theory itself, the core theory underpinning this framework. The philosophical premise underlying this framework is that sensory substitution enables disabled visitors to construct cognitive representations typically dependent on an absent sensory modality [33]. However, this premise remains theoretically contested. Auvray and Myin survey a debate that has persisted in this field for close to fifty years, between the "dominance thesis", which holds that the perception produced by sensory substitution remains fundamentally that of the substituting modality itself, and the "deference thesis", which holds that the nature of this perception should defer to the substituted modality [53]; ultimately, however, they endorse neither of these dominant positions, proposing instead a more nuanced account in which sensory substitution devices transform and extend our perceptual capacities, producing a genuinely novel form of perception that is neither purely tactile nor purely visual. In a similar vein, Proulx and Stoerig observe that although sensory substitution devices have now been developed and tested for nearly fifty years, the phenomenal character of the first-person experience of their users remains a matter of considerable ongoing dispute [54]. Accordingly, although the concept of sensory substitution has been applied in accessible curatorial practice for a number of years, no academic consensus yet exists as to what sensory substitution actually produces in phenomenological terms. While no rigorous consensus has been reached regarding what occurs within this "black box" of sensory substitution, practical evidence provides some support for the deference view. Although this view theoretically holds that visual-to-tactile substitution can produce genuinely visual qualia, a later case study of two long-term expert users of an auditory sensory substitution device similarly found that users reported visual phenomenological experiences [55,56]. At a further level, sensory substitution theory is overly focused on the sensory channel itself: sensory substitution is not merely a problem of replacing sensory channels; it is a problem of replacing perceptual experience. Yet even among disabled individuals who share the same sensory impairment, their needs regarding substitutive information are not uniform. Merabet and Pascual-Leone demonstrate that although both groups have lost vision, different types of blindness, such as congenital and late-onset blindness, are associated with different underlying changes in brain structure [57]. Accordingly, the substitutive information required to compensate for vision is likely to be understood quite differently by these two groups, which requires that co-design processes undertaken when training the large language model involve thorough communication to understand disabled individuals' actual needs, and that different categories of data be classified and weighted accordingly. This philosophical uncertainty carries a direct design implication: the system's framing should avoid claiming to "restore" or "reconstruct" a missing sensory modality, and should instead be described in more epistemically modest terms as providing functional, informational compensation whose phenomenal character remains an open question, while co-design processes must treat congenital and late-onset blindness, and analogous distinctions across other impairment types, as requiring differentiated rather than uniform substitutive strategies.

Moreover, the boundaries of current AI capability constitute a further major challenge for this framework. As noted earlier, the absolute accuracy of conventional consumer-grade iPhone LiDAR sensors is approximately ±1 cm [38]. This nonetheless leaves a considerable gap relative to the classic textbook figure commonly cited for the two-point discrimination threshold, in the range of 2 to 8 mm [58]. In practical implementation, numerous instances will undoubtedly arise in which the precision required touches the boundary of current AI capability; addressing this may require the introduction of complementary methods to optimize the workflow, or

await further technological development. A further issue frequently noted in the application of AI to accessibility is the problem of hallucination. Hallucination poses a categorically different risk within this system than in general-purpose conversational AI, because the population this framework serves faces what recent scholarship terms "limited verifiability" and "asymmetric error costs": a sighted visitor can cross-check an AI-generated description against what they see, but a blind visitor relying on audio or haptic output has no equivalent means of independent verification [59]. This asymmetry is particularly consequential when AI-generated outputs are difficult for disabled users to independently verify or challenge [60]. Accordingly, this framework does not treat hallucination as a uniform risk to be mitigated by a single knowledge-grounding mechanism, but proposes differentiated confidence thresholds and human-oversight requirements across modules, with navigation-critical outputs held to substantially more conservative standards than interpretive or aesthetic content. Finally, and most importantly, this framework must confront the trap of technological solutionism. The preceding discussion has devoted considerable space to arguing that a curatorial accessibility LLM holds substantial potential to integrate existing sensory substitution technologies and thereby deliver a superior accessible experience; yet this argument itself risks falling into precisely the trap of technological solutionism. Morozov defines this as an ideology that reduces complex, messy social realities to problems solvable through purely technical means, thereby diverting critical attention away from the broader social structures that ought to bear greater responsibility for the problem at hand [61]. Shew extends this critique specifically to accessibility technology, arguing that ableism historically originates from a social conception of disability as "deficit", and that technological solutionism represents a contemporary continuation of this mode of thinking by offering technical solutions to social barriers while never questioning whether those barriers themselves warrant scrutiny [62]. The problem is not that technology itself is harmful, but that the very framework of "solving problems through technology" diverts attention, creating the mistaken impression that once a technical solution exists, the deeper social and structural barriers have already been addressed. This framework does not regard the proposed system as a comprehensive solution to museum accessibility, but instead follows the more cautious positioning adopted by comparable accessibility data science frameworks, aiming to narrow a specific, known informational and experiential gap—one that does not touch the deeper architectural, institutional, and attitudinal barriers on which the exclusion of disabled people from cultural spaces ultimately depends. The corresponding design implication is that confidence and precision cannot be treated as uniform system-wide parameters: navigation-critical and haptic-precision-dependent functions must be held to more conservative thresholds than interpretive or aesthetic content, and the system's technical roadmap should treat current AI capability boundaries as a constraint to be designed around, rather than one to be assumed away by future model improvements.

Beyond technical feasibility, a further limitation concerns the transferability of this framework across diverse curatorial contexts, which faces two specific problems. The first is financial: Kagkelidou notes that although many institutions are embracing AI, VR, and AR technologies to enhance their appeal and inclusivity, limited financial resources are the most frequently cited obstacle—57% of respondents identified limited financial resources as a key barrier to adopting new technology [63]. Although the system proposed in this framework may lower average costs of use through strong reusability, the comparatively high upfront investment required may nonetheless constitute a significant barrier; a leasing model for sensory substitution technologies might therefore be considered as a way of serving financially constrained venues. Second, contemporary curation is an extremely complex and diverse field: beyond the most common art galleries and museums, it also encompasses science museums, natural history museums, children's museums, community museums, Indigenous museums, and many others. Falk and Dierking note that the museum experience arises from the interaction of a visitor's personal, sociocultural, and physical contexts, rather than being determined by the exhibition alone [64]. Accordingly, the LLM within this system would need to undergo separate, targeted training for curation across different subject matters and cultural backgrounds—an undertaking of considerable scale. It is therefore recommended that this work proceed incrementally, first prioritizing adaptation to curatorial environments oriented toward the broadest public audiences, before gradually extending to other curatorial contexts as circumstances allow. This suggests that transferability should be treated as a staged design goal rather than an assumed default: institutional partnerships, phased subject-matter adaptation, and flexible

deployment models, such as the leasing arrangement proposed above, constitute concrete next steps rather than incidental afterthoughts.

The final challenge concerns tensions among ethical, cultural, and technical considerations. Beyond the three limitations discussed above, the deployment and dissemination of the framework proposed in this paper will also give rise to a series of deeper ethical, cultural, and technical tensions that cannot, at present, be fully resolved through technical design alone, and that will instead require ongoing negotiation in future practice. The Input Perception Layer of this system involves the collection of various types of information, which may raise concerns regarding privacy and stigmatization—for instance, in relation to the collection of disabled visitors' experiential impressions of an exhibition and various physiological data. Improper methods of collecting or handling such data could harm disabled individuals' interests. Accordingly, following the guidance document issued by the Center for Democracy & Technology, design-level practice should adhere to the principle of data minimization, incorporate privacy considerations proactively rather than reactively, and offer users tiered privacy options—such that even where a user opts for stronger protections, their access to core accessibility functions is not thereby compromised [65]. At the technical level, federated learning and differential privacy techniques have been shown to substantially reduce the risk of exposing raw sensitive data while still processing emotional and physiological data; furthermore, emotional data should be designed to be automatically deleted after use, rather than accumulated into a persistent visitor profile. At the procedural level, this framework's future validation research will need to undergo institutional ethics review, obtain explicit informed consent, and adhere to clearly defined data-use protocols. These safeguards are particularly important because the system may process not only accessibility-related experiential data but also other forms of sensitive information. Accordingly, privacy and data governance should be treated as integral components of the system's design rather than as issues addressed only after implementation.

Given that much of the theoretical foundation adopted in this paper originates from developed-country contexts, cultural transferability remains a significant limitation. For example, the social model of disability emerged from the British disability rights movement, while Grech and Soldatic note that disability studies remains largely shaped by Western European and North American perspectives despite approximately 80% of disabled people worldwide living in the "Global South" [7, 8, 66]. The application of these theories across different contexts may therefore simplify local experiences and overlook specific cultural and historical conditions. Although this paper aims to address "diverse curatorial contexts", its theoretical foundations require further cross-cultural examination. Future development of the framework should therefore treat data governance, consent mechanisms, and theoretical assumptions as context-dependent elements rather than universal principles applicable across all settings.

6. Conclusions

This paper has proposed a conceptual Research through Design framework for an LLM-mediated, multimodal accessibility system that integrates tactile, virtual, augmented, and spatial-audio technologies to support accessible curatorial experiences. The framework positions the Curatorial Accessibility-oriented LLM as a mediating layer that connects curatorial knowledge, accessibility requirements, visitor needs, and multiple sensory output modalities. It is evident that the field under scrutiny in this paper remains at a nascent stage of development. Consistent with the more cautious stance advocated in the preceding discussion, this framework is deliberately bounded in ambition: it offers curators and small-to-medium-sized institutions a conceptual pathway to bridge a specific, identified gap in interpretative and sensory accessibility, without relying on a permanent, dedicated team of specialists. This bounded positioning also reflects several unresolved boundary conditions, including the phenomenological status of sensory substitution, the limits of current AI capabilities, and the framework's uneven transferability across resource levels and cultural contexts, which remain to be clarified rather than resolved. The empirical validation strategy outlined earlier is intended to investigate these conditions. This paper has proposed a conceptual Research through Design framework for an LLM-mediated, multimodal accessibility system that integrates tactile, virtual, augmented, and spatial-audio technologies to support accessible curatorial experiences. The framework positions the Curatorial Accessibility-oriented LLM as

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