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Deriving criteria for inclusive AI in museum environments: an abductive approach and case analysis

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Introduction: This study aims to derive and examine criteria for applying AI technologies in museum environments to secure inclusivity and to examine the structural factors that strengthen or constrain their effects.

Methods: AI-driven inclusive services and products used in museums were classified into five domains: AI-based robots and kiosks, mobile services, online services, exhibits, and data analytics. A total of 20 cases were analyzed using qualitative and quantitative methods. Based on the Principles of Inclusive Design proposed by the Design Council, an abductive approach integrating deductive theory review and inductive case interpretation was employed to derive five criteria: Effortless Accessibility, Personal Adaptivity, User Centeredness, Universal Usability, and Operational Continuity.

Results: The criterion-centered analysis indicates that AI-based inclusivity requires integrated design strategies addressing interaction structures, context-aware adaptivity, user agency, social integration, and operational strategy. The domain-based analysis further shows that strengths and limitations vary across AI technology domains, indicating the need for differentiated adoption strategies.

Discussion and implications: The five criteria form an expanded framework reflecting museum environments where AI mediates visitor experiences. The standardized framework derived in this study enables systematic comparison across cases and can support the planning and evaluation of AI-based inclusive services and products in museums as well as other cultural institutions and public facilities, providing practical guidance for inclusive AI deployment under structural and technological constraints.

KEYWORDS

abductive reasoning, artificial intelligence, inclusive design, inclusivity, museum

1 Introduction

In museums, inclusivity is a highly significant value as the [International Council of Museums \(2022\)](#) defines museums as institutions that are “open to the public, accessible and inclusive.” Inclusivity refers to the principle that all individuals, regardless of their socio-cultural background, age, gender, or physical condition, should be able to participate and engage on equal terms ([Roberson, 2006](#), p. 215; [Zallio and Clarkson, 2021](#), pp. 1–2; [Demirel and Erkiş, 2025](#), p. 2; [Fissi et al., 2025](#), pp. 3–4).

From the perspective that museums are fundamentally conceived as it has to be “inclusive,” inclusivity is an essential obligation. Nevertheless, in practice, many museums have yet to fully reflect inclusivity, resulting in the marginalization of certain groups or individuals.

In this context, museums are endeavoring to address various challenges, such as enhancing inclusivity through the application of advanced technologies (Llamazares De Prado and Arias Gago, 2023, pp. 186–187, 196; Rodrigo et al., 2024, pp. 1–2). For example, digital exhibitions, virtual reality applications, and technology-driven guidance services have enhanced visitor experiences of broader groups. Within this perspective, artificial intelligence (AI), as a representative of today’s advanced technologies, holds substantial potential for addressing issues in museums. AI is being actively leveraged in various areas within the museum sector, including the personalization of visitor experiences, the implementation of preservation technologies, and the analysis of visitor behavioral data (Corsini et al., 2025, p. 1; Suiçmez et al., 2025, p. 14). Therefore, AI in museums can be regarded as mediating systems operating across interpretation, access, participation, and institutional management. In this regard, AI has changed its role from an additional digital add-on to the museum’s core infrastructure. Furthermore, its role is expected to expand further in the future. Recent scholarship suggests that the role of AI in museums is likely to expand in more integrated ways, toward broader functions in visitor engagement, interpretation, participatory learning, and institutional practice (Derda and Predescu, 2025, pp. 533, 543; D’Souza, 2025, pp. 393–395). However, research on whether AI technologies are being appropriately applied to inclusivity challenges in museums remains limited. Consequently, scholarly efforts are necessary to investigate how AI can be effectively leveraged to enhance inclusivity in museum contexts.

Achieving inclusivity requires an approach grounded in inclusive design. Johnson et al. (2010, pp. 275–276) defined inclusive design as a philosophy that seeks to address the full range of users by taking into account variations in abilities and needs across the population, while Carroll and Kincade (2007, p. 294) mentioned that inclusive design has come to be known as the effort to focus on creating environments and products that serve people with diverse physical. Similarly, the Inclusive Design Research Centre explained that inclusive design refers to a design approach that embraces the full spectrum of human diversity, including differences in ability, language, culture, gender, and age (Inclusive Design Research Centre, n.d.), and it is described as “the design of mainstream products and/or services that are accessible to, and usable by, as many people as reasonably possible ... without the need for special adaptation or specialized design” by the British Standards Institution (2005). Therefore, inclusive design can be defined as a design methodology that enables as many people as possible to use products, services, and environments without any discrimination.

In addition, the Design Council (2006) has articulated this approach in the form of the Principles of Inclusive Design. These principles consist of placing people at the heart of the design process; acknowledging diversity and difference; offering choice where a single design solution cannot accommodate all users; providing for flexibility in use; and providing buildings

and environments that are convenient and enjoyable to use for everyone. The principles have served as practical guidelines to integrate inclusivity within design processes systematically. However, recent cases show that the integration of AI in museums can introduce new risks that fall outside the scope of the traditional inclusive design principles. For instance, the robot art critic “Berenson,” which evaluates artworks by analyzing visitors’ facial expressions through AI-driven emotion recognition algorithms (Munro, 2016), could be regarded as a positive example of inclusive design under existing principles, as it appears to provide adaptive and responsive interpretation based on user input. However, in practice, such systems may homogenize diverse visitor responses by privileging majority emotional patterns and marginalizing atypical or culturally specific expressions. According to previous study, it is mentioned that facial configurations are not reliable displays of inner emotions across context, person, and culture and inferring emotion from facial movement is not straightforward (Barrett et al., 2019, p. 46). It occurs a difficulty in terms of inclusivity due to the demographic imbalance of facial-processing datasets, which are often skewed toward Western, white, young, and male faces. Therefore, the bias lets models learn majority features more readily than those of underrepresented groups (Hupont et al., 2022, p. 8). In cultural heritage contexts, this problem becomes especially significant because bias in AI pipelines may further intensify the problem (Foka and Griffin, 2024, pp. 6,125, 6,127), as such bias can enter at multiple stages, from data selection and annotation to design, evaluation, deployment, and user interaction (Foka et al., 2025, pp. 5,835, 5,839).

This illustrates how AI can, at times, override individual differences rather than support them, indicating that principles developed in pre-AI contexts are insufficient to address algorithmically mediated museum experiences. Building upon these principles, this study adopts an exploratory and abductive approach to develop and examine an analytical framework for evaluating how AI technologies may support or constrain inclusivity at the design and system level. Therefore, the primary objective of the study is to derive criteria for inclusive AI in museums by extending the Principles of Inclusive Design to AI-mediated contexts. The secondary objective is to examine the applicability of these criteria through cross-case analysis of AI-based museum services and products for inclusivity. Accordingly, this study addresses the following research questions: RQ1. What criteria can be derived to assess inclusivity in AI-mediated museum environments? RQ2. How are these criteria supported or constrained across different domains of AI application in museums? RQ3. What design and operational implications emerge from the cross-case analysis of AI-based inclusive practices in museums?

2 Methods

This study adopted an exploratory, abductive, and multiple-case comparative design. This design was selected as insufficiently theorized phenomenon, such as AI-based inclusivity in museums, requires conceptual development rather than confirmatory testing (Edmondson and McManus, 2007, pp. 1,160–1,161). Also, abductive approaches allow the study to move iteratively between

existing principles and empirical case interpretation, thereby developing criteria that account for the specific conditions (Dubois and Gadde, 2002, pp. 554–555). The multiple-case comparative design further enables the analysis of recurring patterns, contrasts, and domain-specific variations (Eisenhardt and Graebner, 2007, pp. 25–27) across AI applications.

Alternative approaches, such as interviews, surveys, and observations, would be valuable for examining analyses of visitor-perceived aspects and responses. In museum evaluation research, these methods are commonly used to examine how visitors experience and interact with a specific museum program or exhibition (Nelson and Cohn, 2015, pp. 27–30). However, as the aim of this study is to develop a cross-domain framework for evaluating AI-mediated inclusivity at the design-level, this study prioritizes conceptual development and comparability, while recognizing that future research would empirically and longitudinally examine the related cases from visitors' perspectives through the proposed criteria. This research design is based on the following methodological assumptions. First, AI-based museum services and products can be compared at the level of design, interaction, and operation. Second, inclusivity can be assessed at the design-level through abductively-developed criteria. Third, a framework can improve transparency and comparability across cases. These assumptions define the scope of the study as an analysis of design-level inclusivity, rather than as a measurement of perceived inclusivity.

Grounded in the five Principles of Inclusive Design by the Design Council (2006), this study conducted a comprehensive qualitative literature review on the use of AI technologies to enhance inclusivity in museums. Based on the collected data, we derived five criteria for examining how inclusivity may be supported in AI applications within museums, and refined these criteria through an abductive reasoning process. In the analysis, each case was examined in terms of its possibilities and limitations from the perspective of the principles, which served as the deductive foundation for establishing the criteria. At the same time, through an inductive approach, we identified the key factors that should be considered when applying AI technology to enhance inclusivity in museums. This process was iterative, and the cases were analyzed using the constant comparative method, ensuring the criteria were sufficient to achieve theoretical saturation. During the process, a total of 20 cases in 5 domains were organized using a standardized analytical framework for systematic comparison. Each table includes the case title, image, and the potential and critical evaluation identified from the criteria (see [Supplementary Material](#)). Based on this, both qualitative and quantitative evaluations were subsequently conducted to examine how inclusivity was implemented across cases, enabling criterion-centered and domain-based analyses, generating key discussion points of the study.

2.1 Domains

This study examined the application of AI technologies in museums and the related environment, focusing on their potential to enhance inclusivity, and categorized them into five core domains. Drawing on Cambridge (n.d.)'s definition of inclusivity as “the fact of including all types of people, things, or ideas and treating them all fairly and equally,” this study analyzed cases in museum contexts that aim to enhance inclusivity in accordance

with this definition. The 20 cases analyzed in this study were selected according to the aim of capturing variation across AI-mediated inclusive museum practices and identifying patterns, strengths, and limitations. Cases were included when they met the following four criteria: piloted or implemented in museum or cultural heritage contexts; involved AI-based technologies; were used to enhance inclusivity; documented publicly and sufficient information was available for analysis. Given the purposive sampling process, the findings should be understood as conceptual insights that provides analytical insights for evaluating AI-based inclusivity in museums.

The cases were categorized into five AI technology domains and the identified domains are as follows. First, AI-based robots and kiosks refer to physically deployed AI systems designed to provide visitor guidance, respond to inquiries, and deliver personalized information. Second, AI-based mobile services encompass services accessible via personal devices such as mobile applications, audio guides, or wearable devices, allowing visitors to engage with exhibitions and programs despite physical or mobility limitations. Third, AI-based online services extend inclusive access beyond the physical museum space, including AI-powered curation, virtual tours, and chatbots on museum websites. Fourth, AI-based exhibits integrate AI technologies directly into exhibition content, enabling visitors with diverse sensory and cognitive needs to participate equitably. Finally, AI-based data analytics involves technologies that, although not interacting directly with visitors, analyze visitor flow, dwell time, congestion, and other behavioral data to support administrators in designing and managing more inclusive environments. This classification enabled comparison across different forms of AI-mediation while preserving sensitivity to their distinct operational roles.

2.1.1 AI-based robots and kiosks

AI-based robots and kiosks refer to systems that are physically deployed in museum spaces to support visitor guidance, inquiry response, and personalized information delivery. In this study, we examined the following representative technologies: QI at the National Museums of Korea, Pepper at the Smithsonian museums in the United States, the AI Suitcase at the National Museum of Emerging Science and Innovation (Miraikan) in Japan, and the AI Kiosk at the National Museum of Korea.

QI and Pepper are autonomous guide robots that navigate within museum environments. QI utilizes voice recognition and multilingual functions to guide visitors to exhibition areas and facilities and to serve basic and everyday inquiries. Similarly, Pepper responds to visitor questions and introduces exhibitions through conversations, gestures, and a touch-screen interface. The AI Suitcase is a luggage-shaped navigation robot that supports mobility for visually impaired visitors by recognizing its surroundings using LiDAR and RGB-D cameras ([Figure 1](#)). It assists visitors by guiding them to the destination through sound and vibration signals to ensure safe movement and delivering information about the exhibits nearby. The AI Kiosk is a barrier-free interface kiosk for supporting visitors with visual, auditory, and mobility impairments ([Figure 2](#)). This kiosk is equipped with inclusive features such as voice guidance, braille keypads, high-contrast screens, and a sign-language avatar.

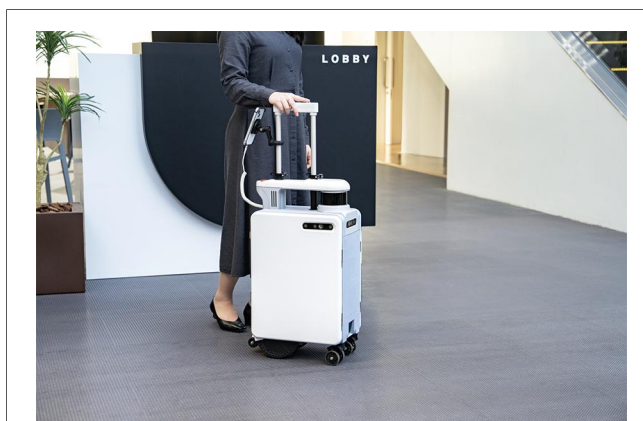


FIGURE 1

This figure depicts the in-use scenario of the AI suitcase deployed at Miraikan. Reprinted with permission from “Miraikan Accessibility Lab.” by Miraikan – The National Museum of Emerging Science and Innovation, © Miraikan/JST. All rights reserved, <https://www.miraikan.jst.go.jp/en/lab/AccessibilityLab/>

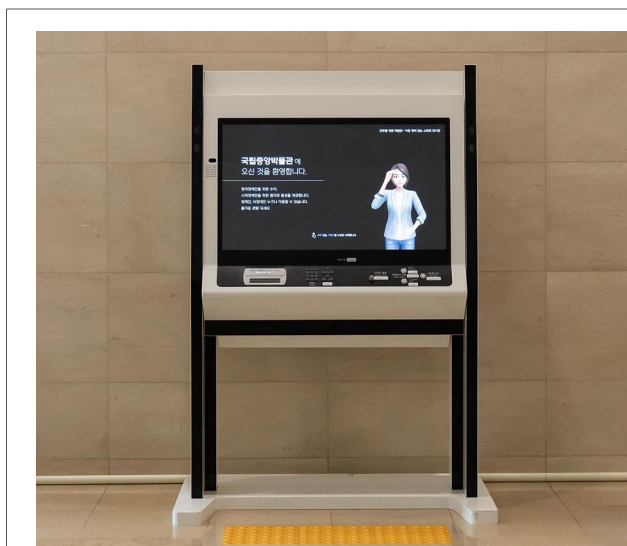


FIGURE 2

This figure presents the in-use scenario of the AI kiosk at the national museum of Korea, featuring interaction by a wheelchair user. Reprinted with permission from “국립중앙박물관 맞춤형 전시 안내 스마트 키오스크의 접근성 기능 개선” by National Museum of Korea, © National Museum of Korea. All rights reserved, https://www.museum.go.kr/doc_viewer/skin/doc.html?fn=4737b48b2a4212dd75a52289880f3b75.hwp&rs=/uploadfile/doc_viewer/preview/html/

2.1.2 AI-based mobile services

AI-based mobile services direct systems and applications that operate through visitors' personal devices, such as smartphones or mobile audio guides. These services support personalized tours, accessible interpretation, and multimodal content delivery for larger inclusivity. In this study, we examined the following representative cases: the Smithsonian AI-powered audio guide, Museumfy, and Amuseapp as general-purpose visitor-centered platforms; Ally for Museums (Ally) as an AI application developed specifically to support visually impaired visitors; and

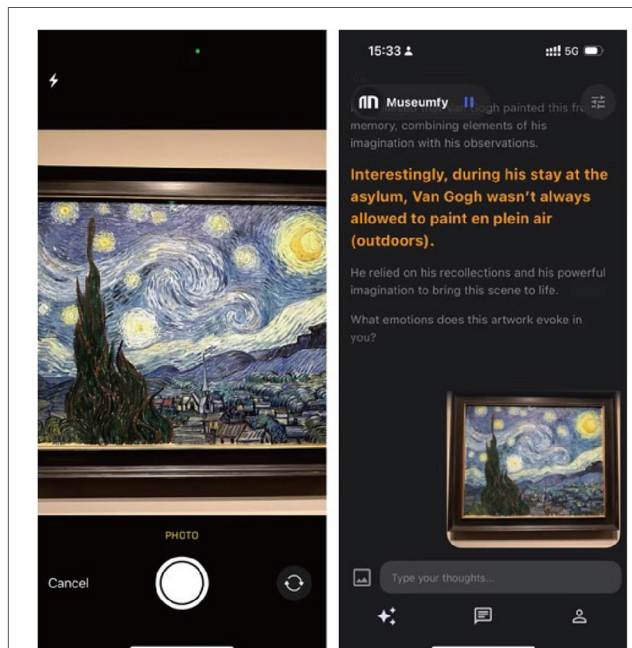


FIGURE 3

This figure provides an example of the user interface of Museumfy, where visitors interact with the application using natural language after taking a photo of the exhibit. Reprinted with permission from “Museumfy – Your Personal AI Museum Companion | Discover Art & History” by Museumfy, © Museumfy. All rights reserved, <https://www.museumfy.com/>

the AI-based Korean Sign Language (KSL) translation service deployed at the National Gwangju Museum.

The cases of the Smithsonian AI-powered audio guide in collaboration with Smartify, Museumfy, and Amuseapp illustrate the role of AI in generating personalized tours, multilingual content, and accessibility. The Smithsonian's AI-powered audio guide creates customized itineraries according to visitor preferences, Museumfy automates descriptive metadata by taking a photo of the artwork, and Amuseapp supports rapid delivery of multilingual audio guides and tailored routes inside museums (Figure 3).

The cases of Ally and the KSL translation service are particularly aimed at broadening inclusivity for visitors who may otherwise face physical barriers to engagement. Ally provides conversational, camera-based artwork descriptions on any smartphone without special hardware for the visually impaired. The AI-based KSL translation service of the National Gwangju Museum (Figure 4) uses 3D motion-capture data and a sign-language avatar to deliver accurate KSL translations of exhibition texts, and incorporates adjustable visual settings to support visitors with auditory needs.

2.1.3 AI-based online services

AI-based online services refer to digital systems that extend museum accessibility beyond the physical exhibition space, enabling visitors to explore collections, receive guidance, and access interpretive materials remotely through virtual tours and web-based tools. In this study, we examined the following representative technologies: Clio 1.0 of the London Museum, the

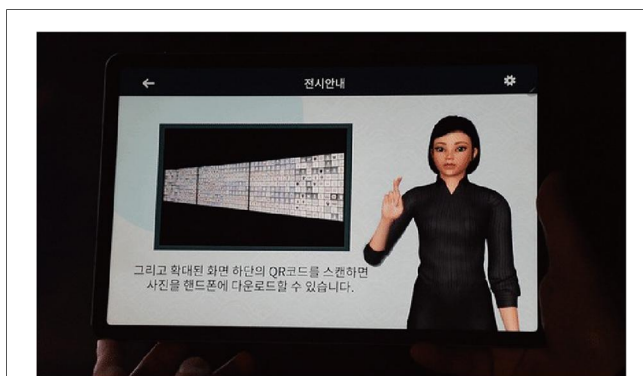


FIGURE 4

This figure displays an AI-powered avatar translating exhibit descriptions into Korean sign language. Reprinted with permission from “인공지능, 박물관 찾는 청각장애인의 ‘귀’가 되다” by AI Times, © AI Times. All rights reserved, <https://www.aitimes.com/news/articleView.html?idxno=141188>

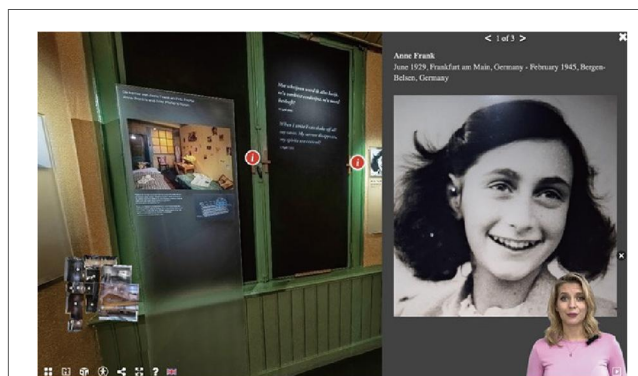


FIGURE 6

This figure depicts an AI-powered avatar integrated into the virtual tour on the Anne Frank house website. Reprinted with permission from “The Anne Frank House launches a 3D virtual tour” by Anne Frank House, © Anne Frank House. All rights reserved, <https://www.annefrank.org/en/about-us/news-and-press/news/2024/11/14/the-anne-frank-house-launches-a-3d-virtual-tour/>

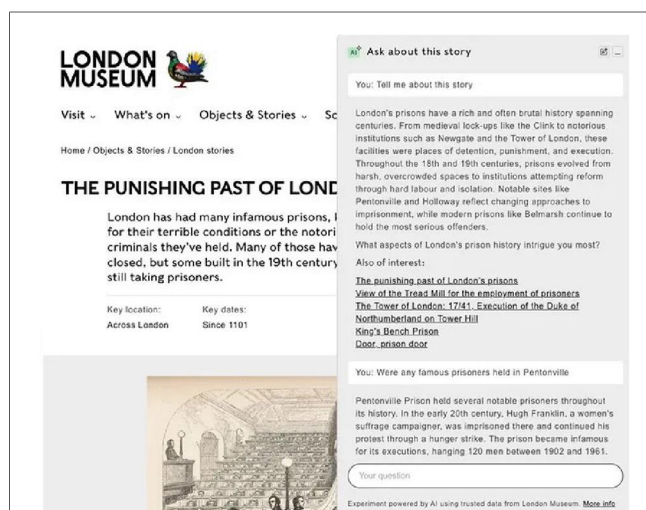


FIGURE 5

This figure presents the web interface that describes the museum collections at the London museum. Reprinted with permission from “Introducing our conversational search agent” by Trish Thomas, © London Museum. All rights reserved, <https://www.londonmuseum.org.uk/blog/introducing-our-conversational-search-agent/>

Microsoft’s collaboration with the Rijksmuseum uses AI to generate detailed, emotionally rich descriptions of artworks at scale, enabling more equal access to extensive museum collections for visually impaired visitors. The AI-avatar-guided virtual tour developed by the Anne Frank House (Figure 6) employs a digitally cloned image and voice to guide visitors through a fully navigable 3D representation of the historic Annex in four languages, making the site accessible to audiences who cannot physically visit the museum.

2.1.4 AI-based exhibits

AI-based exhibits refer to cases in which AI is embedded directly into the exhibition environment, allowing visitors with diverse sensory abilities and needs to engage with artworks and museum content in new, multimodal ways. In this study, we examined three representative examples of such AI-integrated exhibition practices: “Touch: Beyond Vision” in London, “Framing Inclusion: AI Art Response to Burt’s Educational Standards” by the University College London (UCL), and “Talk to Dead Animals” at the Museum of Zoology at Cambridge.

“Touch: Beyond Vision” employed AI-driven technology to convert digital images into meaningful three-dimensional tactile forms, enabling visually impaired and also non-visually impaired visitors to experience visual culture through touch (Figure 7). “Framing Inclusion: AI Art Response to Burt’s Educational Standards” is a co-creation project in which young people with diverse physical abilities used AI to reinterpret and critique the eugenic legacy of Cyril Burt’s educational tests. By transforming historical assessment tools through generative AI, the project exhibited technological bias and repositioned disabled participants as active creators of new inclusive narratives. “Talk to Dead Animals” transformed traditionally static natural history specimens into interactive conversational agents powered by AI, allowing visitors to communicate with preserved animals.

Living Museum project utilizing the objects’ data of the British Museum, the Cleveland Museum of Art’s AI-enabled website, the Rijksmuseum’s open collection in collaboration with Microsoft’s Copilot, and the AI-avatar-guided virtual tour developed by the Anne Frank House.

Clio 1.0 and the Living Museum enhance online discovery and enable interactions with museum collections through AI technology. Clio 1.0 enables natural-language exploration of the London Museum’s records by synthesizing information into paragraph-style answers (Figure 5), while the Living Museum allows visitors to converse with approximately 1.2 million objects through a generative AI model trained on data. The Cleveland Museum of Art’s website offers AI-enabled features such as visually similar artwork search (Extend the Art) and interactive tools (Share Your View), built on an inclusive perspective that prioritizes scalable digital engagement.



FIGURE 7

This figure captures hands-on interaction with an AI-enabled exhibit that transforms two-dimensional artworks into three-dimensional tactile forms at the exhibition “touch: beyond vision”. Reprinted with permission from “Touch: Beyond Vision” by Touch: Beyond Vision, © Touch: Beyond Vision / Carveco. All rights reserved, <https://touch-beyond-vision.com/>

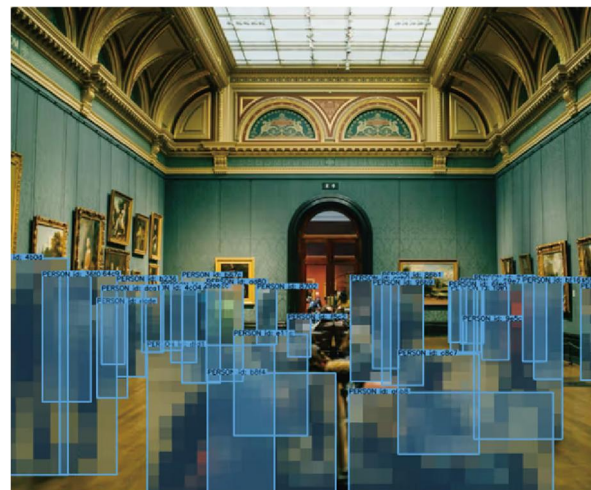


FIGURE 8

This figure visualizes how Isarsoft perception analyzes visitor flow using AI-based monitoring technology. Reprinted with permission from “Touch: Beyond Vision” by Touch: Beyond Vision, © Touch: Beyond Vision / Carveco. All rights reserved, <https://touch-beyond-vision.com/>

2.1.5 AI-based data analytics

AI-based data analytics refer to technologies that do not interact directly with visitors but support museums in creating more inclusive environments through back-end services, such as accessible content production and data management. In this study, we examined three representative systems: Codemantra’s accessibilityInsight™ (Codemantra), Isarsoft Perception, and BriefCam.

Codemantra provides AI-driven document processing that converts images, exhibition-related and archival materials into accessible digital formats that are compliant with the Web Content Accessibility Guidelines (WCAG) and Section 508 standards. This enables museums to broaden access to previously inaccessible collections for visitors with various physical characteristics, while streamlining internal workflows. Isarsoft Perception and BriefCam, as a group of AI-based video analytics systems, generate real-time insights into visitor flow, congestion, and movement patterns by analyzing existing camera feeds. Isarsoft Perception, implemented at the Wien Museum, uses AI-powered video analytics to track visitor counts, congestion, and movement patterns in real time (Figure 8). BriefCam, used at the Glenstone Museum, applies automated people counting and behavior analytics to control visitor flow and improve security across its indoor-outdoor campus through AI technology. These systems improve overall accessibility and visitor experience by informing decisions on staffing, wayfinding, and spatial layout.

2.2 Inference of criteria

Prior to the derivation of the criteria, this study employed the Principles of Inclusive Design proposed by the Design Council (2006), which have been widely utilized as reliable guidelines, for a deductive analysis of the cases. On the other hand, an inductive

review of practical cases revealed limitations in the direct applicability of existing principles, particularly in algorithmic mediation, dynamic personalization, and real-time interaction that are central to AI-enabled museum experiences. Therefore, the principles were found to be insufficient for addressing the specific aspects and challenges of enhancing inclusivity in museum contexts that increasingly rely on AI technologies.

Accordingly, this study adopted an abductive approach. Abductive reasoning allows for the derivation of plausible explanations and new hypotheses when existing theories or empirical patterns alone are insufficient (Rapanta, 2018, pp. 294–295). Particularly, Abductive reasoning is suitable for design contexts characterized by incomplete information and emerging technologies, where abstract intentions must be translated into concrete solutions through design synthesis processes (Lu and Liu, 2012, p. 143). In this sense, abductive reasoning enables connections between theoretical principles and situated practices. This process aligns with the abductive research process by Kovács and Spens (2005, p. 139), in which abductive inquiry begins with observations that cannot be fully explained by existing theories and proceeds through an iterative process of theory matching and systematic combining. Through this process, new hypotheses or propositions are generated to better explain emerging phenomena. Also, unlike deductive or inductive reasoning, abductive reasoning maintains an open attitude toward new evidence and emphasizes value creation through iterative interactions with real-world contexts (Dreamson and Khine, 2022, p. 405).

Although various theories and principles on inclusivity have been introduced and utilized, the abductive approach, in the context of museums facing a new trend of integrating AI technology, allows for the integration of theoretical principles and empirical insights, enabling the development of criteria that capture the key concepts of AI-led inclusivity. Through the abductive process that repeatedly moves between these theoretical principles and empirical case analysis, this study

derived a set of criteria that reflect the already established principles and the specific characteristics of AI technology integrated within museums. Based on this process and derived criteria, the researchers systematically evaluated and analyzed cases corresponding to five distinct domains. The following criteria were used to guide the analysis:

- Effortless Accessibility: ensuring easy and barrier-free access
- Personal Adaptivity: responding to individual needs and contexts
- User Centeredness: positioning visitors at the center, not technology
- Universal Usability: providing a non-stigmatizing experience for all
- Operational Continuity: ensuring inclusivity as a default and continuous condition

The five criteria proposed in this study serve as necessary within the defined scope of this research. They were derived because they repeatedly emerged at the intersection of existing inclusive design principles and AI-specific case characteristics, and the framework does not exhaust all dimensions of museum inclusivity. Broader issues such as power, governance, community authority, and ethics were not adopted because they operate primarily at institutional and political levels that exceed the design-level scope of this study. In particular, as prior studies have demonstrated that qualitative inference is effective for verifying criteria and generating insights (Lee et al., 2020, p. 42), this approach was employed to reinforce the analytical consistency of the criteria development process.

Furthermore, the study quantitatively assessed all cases using the established criteria and examined the extent to which each case reflected the five inclusivity criteria derived through the abductive process. Each case was assessed on a five-point scale: from 1, indicating very limited evidence, to 5, indicating very strong evidence to the criterion. The five criteria were applied with equal weight because the study did not assume a hierarchy among criteria. Initial scores were based on each case's documented features, inclusivity potential, and limitations. Scoring discrepancies appealed on the initial scores were

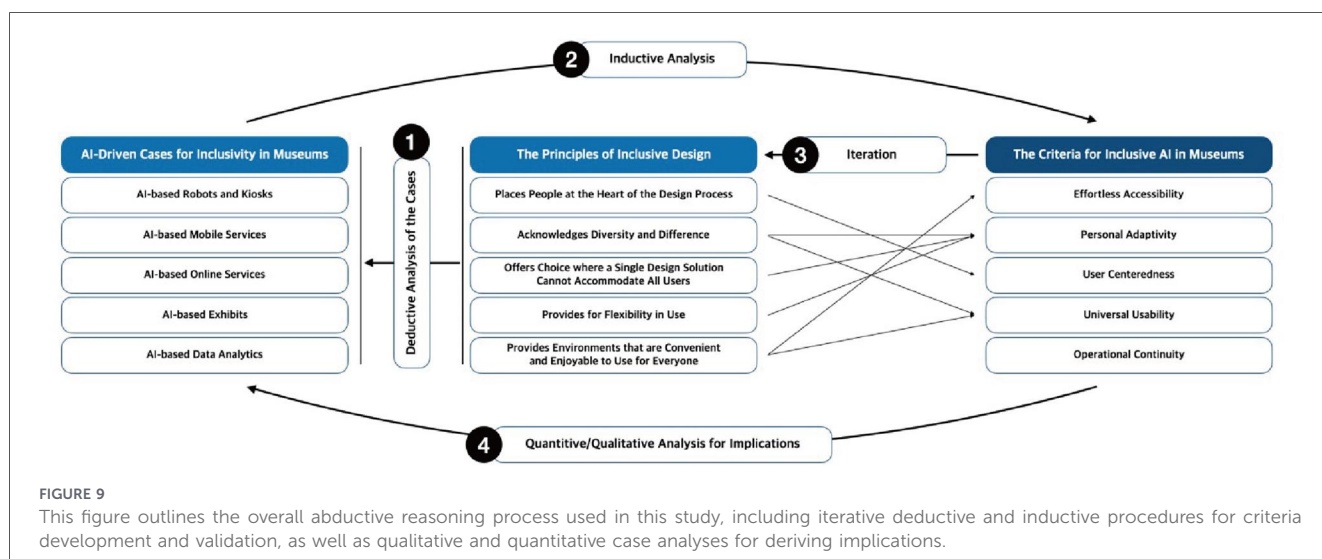
discussed and revised through an internal calibration process among researchers to support consistent interpretation. Therefore, the final scores reflect consensus-based interpretive judgments that enable systematic comparison. The entire analytical process was conducted iteratively and systematically, thereby enabling the establishment of robust and rigorous evaluation criteria (see Figure 9).

2.2.1 Effortless accessibility

In a museum environment, accessibility is the most basic prerequisite for visitors to participate in exhibitions and information. Previous studies have also highlighted that when visitors who require specific forms of support are asked to exert excessive effort or seek additional assistance to access exhibition content, this can act as a factor limiting their participation (Mesquita and Carneiro, 2016, p. 376). In particular, with the recent introduction of AI technology in the museum environment, accessibility is no longer limited to physical or spatial perspectives, but has expanded to encompass interactions mediated by digital interfaces and algorithms. In this context, accessibility, which enables visitors to engage with exhibition experiences with minimal effort, plays a key role in creating an inclusive museum environment.

Therefore, this study uses Effortless Accessibility to determine whether visitors can use AI-based museum content or services easily and intuitively. This is for content designed to enhance inclusivity without needing extra learning, special skills, or additional assistance. It includes minimizing the burden not only in terms of physical accessibility, but also across perceptual, cognitive, linguistic, and interactive dimensions.

This criterion is conceptually linked to the principle of “providing environments that are convenient and enjoyable to use for everyone” among the principles of inclusive design presented by the Design Council (2006). However, these principles mainly focus on accessibility at the environmental level, such as space composition, ease of use, and physical comfort, and do not sufficiently address the complex accessibility problems arising from the interactions mediated by



AI technology. AI-based content or services feature new interaction elements, such as how algorithms work, multi-modal interfaces, voice and sign language input, automatic translation, and adaptive display, which can create new barriers that are not adequately explained by the existing principles.

Effortless Accessibility was derived with these limitations in mind. It focuses on evaluating whether AI technology actively removes perceptual, cognitive, linguistic, and interactive barriers. In other words, it is a criterion for examining whether the AI system minimizes access burdens for visitors and supports participation in various ways, going beyond mere ‘convenience.’

2.2.2 Personal adaptivity

The background, ability, and purpose of visitors to the museum are diverse, and it is difficult for the same exhibition environment or service to operate in the same way for all visitors. Previous studies have also pointed out that an inclusive approach is a design approach that seeks to accommodate a broad spectrum of users by addressing differences in age, cultural background, competence, expectations, and physical or cognitive conditions (Pietroni et al., 2021, p. 567). In particular, as museums function as public spaces that accommodate a wide range of visitors, responses tailored to individual characteristics constitute a key element for expanding inclusivity.

Accordingly, in this study, Personal Adaptivity refers to the degree to which AI-based inclusive elements introduced in museums recognize the individual characteristics and needs of visitors and adjust experiences accordingly. This includes not only whether these elements function in a way that suits the needs of each visitor, but also whether AI technology detects and adapts to the user’s sensory preferences, linguistic needs, mobility constraints, and cognitive characteristics in real time.

This criterion is related to the Principles of Inclusive Design set out by the Design Council (2006), “acknowledging diversity and difference,” “offering choices where a single design solution cannot accommodate all users,” and “providing for flexibility in use.” However, existing principles are mainly based on providing static options for users to choose or adjust on their own, which does not fully reflect the characteristics of AI technology-based interactions that identify visitors’ states or contexts through data collection and algorithmic analysis. Such personalized adaptation was not fully considered within the context of inclusive design before the adoption of AI technologies.

Based on these limitations, the Personal Adaptivity criterion was established to examine whether more sophisticated and practical inclusivity is realized by providing a variety of options for visitors to meet their requests and by further personalizing experiences according to visitors’ characteristics and situational contexts through AI technology.

2.2.3 User centeredness

The starting point of the discussions of inclusivity in museums is always the visitors. As AI technology is deeply integrated throughout exhibitions and museum environments, visitor centrality extends to questions concerning what role the technology will play in the actual use process. In particular, in

situations where AI predicts or provides recommendations for visitors’ behavior and adjusts the flow of interactions, the possibility and concern that the technology itself may lead or distort the experience must be considered together.

In this context, User Centeredness is conceptually connected to the principle of the Design Council (2006) that “places people at the heart of the design process.” This principle has emphasized the importance of design attitudes that use users’ needs and experiences as a starting point. When applied to contemporary museum contexts, it is possible to recognize the problem that various AI systems designed for inclusivity go beyond their original supportive functions by reducing visitors’ options or interpretive agency, or by creating a situation in which the logic of technology leading the experience may occur. In particular, AI, as one of the cutting-edge technologies, can evoke distinct emotional responses among visitors, continue to operate beyond the immediate exhibition context, and indirectly affect visitors’ experiences through algorithmic judgments, interface signals, recommendation methods, and automated decision-making processes.

Accordingly, in this study, User Centeredness was established as a criterion for evaluating whether AI technology does not infringe on the subjectivity and judgment of visitors, even in the actual use process, and remains in a role that supports and expands the viewing experience. This criterion is distinct from the existing principles focused on user empathy, as it conceptualizes User Centeredness as a condition that must be continuously monitored during operation and use, rather than as a consideration limited to the design stage alone.

2.2.4 Universal usability

An inclusive museum environment should ensure that a variety of visitors can use the space and content without discrimination. However, ensuring accessibility alone does not complete inclusivity. If visitors are visually identified or socially separated because they use certain support, this can lead to another form of exclusion.

From this perspective, Universal Usability is linked to the principles of “acknowledging diversity and difference” and “providing environments that are convenient and enjoyable to use for everyone” outlined by the Design Council (2006). However, as AI-based technologies have been integrated into museum experiences, additional issues of stigma and technological visibility have emerged, as mentioned above. For example, AI-based support such as AI Suitcase and KSL translation services can greatly expand inclusivity, but at the same time, they also pose a risk of making certain visitors visibly identifiable as ‘special’ or ‘in need,’ or of inducing segregated experiences. This issue has not been explicitly addressed in the existing discussion of environmental usability.

Accordingly, Universal Usability evaluates whether AI-based support is seamlessly integrated into the general viewing experience without visibly distinguishing or labeling visitors. This criterion determines inclusivity based on whether the support provided by AI operates in a socially smooth and natural manner, allowing all visitors to share the same space and experience.

2.2.5 Operational continuity

AI-based inclusivity is not only a question of whether technology has been introduced, but also a question of whether it is continuously operated. In many cases, using advanced technologies as well as AI technology, various services and contents are often operated for specific exhibitions, pilot projects, or limited periods for various reasons, which makes it difficult to achieve the original objectives and increases the likelihood that such initiatives are reduced to one-time demonstrations.

Existing principles have primarily focused on the presence of functions or design intentions and have paid relatively little attention to whether these functions are continuously managed in the actual operation process and improved based on feedback or updates. However, through the abductive case analysis, it was revealed that inclusivity can be easily weakened if operation, management, and maintenance are not continuously performed even after technology deployment. In museum environments, it is necessary to respond to changes in operating conditions such as exhibition replacement, manpower changes, contract modifications, system errors, and software updates; otherwise, it becomes difficult to ensure sustained access and participation.

Operational Continuity, derived accordingly, is a criterion for evaluating whether AI technology can contribute to the expansion of inclusivity in the museum environment from a long-term perspective. This criterion includes the capacity for hardware and software upgrades, the stability of the operating system, and the ability to respond to unexpected situations, and differs from existing principles by defining inclusivity as a matter of continuous practice rather than a one-time implementation.

3 Results

3.1 Criterion-centered analysis

This section analyzes the cases based on the criteria derived through an abductive process, examining the extent to which

each criterion is consistently implemented in museum contexts for inclusivity, as well as identifying which criteria are relatively weak or unevenly applied. This criterion-centered analysis goes beyond comparing performance across domains by synthesizing score distributions and case characteristics for each criterion, and aims to determine which criteria are actively addressed in AI-based inclusivity practices and, conversely, which remain at an experimental stage. This provides foundational context for interpreting how each domain forms specific configurations of inclusivity in the subsequent domain-centered analysis. The mean scores and standard deviations calculated for each criterion are presented below as Figure 10. The quantitative results are presented as descriptive indicators to support interpretive comparison across cases and domains.

3.1.1 Effortless accessibility

Effortless Accessibility recorded the highest overall mean score among the five criteria, with a moderate level of variance across cases, indicating that it is a criterion commonly secured across diverse domains and cases. When AI technologies are introduced into museum environments for inclusivity, accessibility approaches such as simplifying access pathways and facilitating information acquisition were considered as priorities. In particular, as accessibility-oriented UI and UX are implemented across multiple channels, such as mobile devices and websites, conditions have been established that allow visitors to access content without requiring additional learning or complex processes. Moreover, with advances in AI technologies, reliance on operational structures has been relatively reduced, making it possible for accessibility to be secured to a certain extent through technical design alone. This is interpreted as contributing to the stable performance observed for Effortless Accessibility. These results suggest that Effortless Accessibility is one of the most important criteria in the implementation of AI-based inclusivity, and is widely prioritized in design considerations.

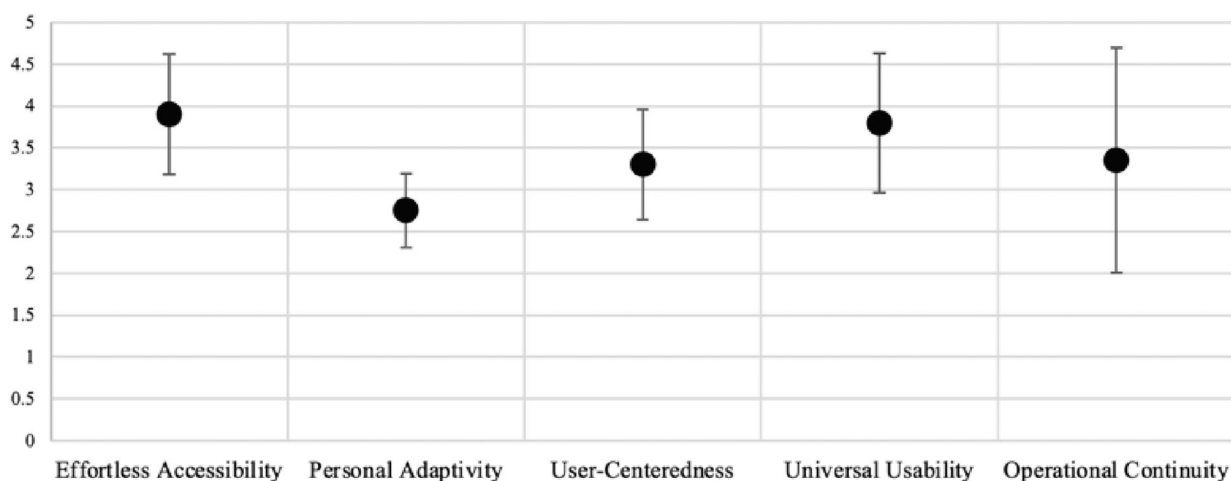


FIGURE 10

This figure summarizes the mean values and standard deviations for each inclusivity criterion.

3.1.2 Personal adaptivity

Personal Adaptivity exhibited the lowest mean score among all criteria, while also showing low variance across cases, indicating that it is a generally weakly implemented criterion. This is because functions that recognize visitors' conditions, contexts, sensory characteristics, and levels of understanding in real time and adjust exhibitory experiences accordingly are not only technically complex but are also often insufficiently considered into service in terms of the scope of adaptivity. In many cases, personalization remains limited to basic functions such as language settings or content selection, and does not extend to forms that interaction structures or information presentation methods vary across individuals. In addition, real-time adaptation based on personal data requires complex conditions, including ethical evaluations, legal issues, technical infrastructure, and operational capacity, which further constrain active implementation in museum contexts. As a result, although Personal Adaptivity is a core element of inclusivity, it emerged as the criterion with the highest barriers to implementation in practice.

3.1.3 User centeredness

User Centeredness showed a mid-range mean score among the overall criteria, with variations in implementation levels observed depending on cases. In some cases, user agency was strengthened by operating structures based on visitor-driven demands, represented by visitors' choices, questions, and interpretations. In contrast, in other cases, the flow of information provision and the structure of the experience were predetermined by system logic, maintaining a tendency toward one-way communication. This difference is interpreted as being largely influenced by design perspectives regarding the role of technology in the visitor experience, namely whether technology functions as an agent that organizes the experience or as a tool that supports visitors' activities. That is, the implementation of User Centeredness is determined less by specific domains and more by design-stage decisions regarding to whom experiential control is assigned, which served as a primary factor contributing to variance across cases.

3.1.4 Universal usability

Universal Usability demonstrated a high mean score comparable to that of Effortless Accessibility, but exhibited a relatively larger standard deviation. In particular, when technologies operated in the background without being directly exposed to visitors, there was a lower likelihood of segregating specific users, and non-stigmatizing and socially integrated experiences tended to be maintained. In contrast, in cases where AI-based technologies were designed to require the use of separate devices, the use of support became externally visible, increasing the chances of experience separation and risks of stigmatization. These results indicate that Universal Usability is highly dependent on the design direction of AI technologies and how they are used and embedded within environments. Therefore, Universal Usability can be interpreted as a criterion whose performance is determined not by technical capability

itself, but rather by modes of delivery and the degree of spatial integration within museum settings.

3.1.5 Operational continuity

Operational Continuity was the criterion that exhibited the greatest variance across cases, with some cases demonstrating high scores while others remained at very limited levels. This difference was found to be strongly dependent on operational structures, such as whether systems were managed as permanent installations or limited to project-based implementations. When long-term operation was assumed with continuous updates and maintenance systems, sustained service provision and system improvement were possible over multiple years. However, when systems were implemented in the form of exhibitions or experimental projects, strong tendencies were observed for documentation of outcomes and post-project expansion to be discontinued after termination. This suggests that inclusivity cannot be sustained through short-term functional implementation alone and that organizational-level operational strategies and resource allocation constitute key conditions for ensuring continuity.

3.2 Domain-centered analysis

This section analyzes the structural characteristics of inclusivity implementation by technology type, focusing on how each AI technology domain realizes the five inclusivity criteria in different combinations. Whereas Section 4.1 presented levels of implementation difficulty and overall distribution patterns by criterion, this section aims to examine how those results are configured based on domain-specific characteristics. The heatmap visualizing case-level scores and mean values for each domain is presented below (see [Figure 11](#)).

3.2.1 AI-based robots and kiosks

In the AI-based robots and kiosks domain, Operational Continuity emerged as the most prominent strength, whereas Personal Adaptivity showed relatively low performance. This is largely because these technologies are often operated as permanent or long-term installations that are physically embedded within museum spaces, and because they involve integrated hardware and software systems that require both high initial implementation costs and long-term operational expenditures. As a result, maintenance systems and operational manuals tend to be institutionally established. For example, QI, AI Suitcase, and AI Kiosk are designed to operate stably through continuous updates even amid exhibition changes or staffing transitions, enabling long-term operation. In contrast, such systems often rely on predefined scenarios and fixed interfaces, which impose structural constraints on real-time adjustment of interactions according to individual visitor characteristics or situational contexts. Accordingly, while Effortless Accessibility and User Centeredness demonstrated mid-level performance, limited patterns were repeatedly observed for Personal Adaptivity. In the case of Pepper in particular, although responsive interaction exists, its operation is

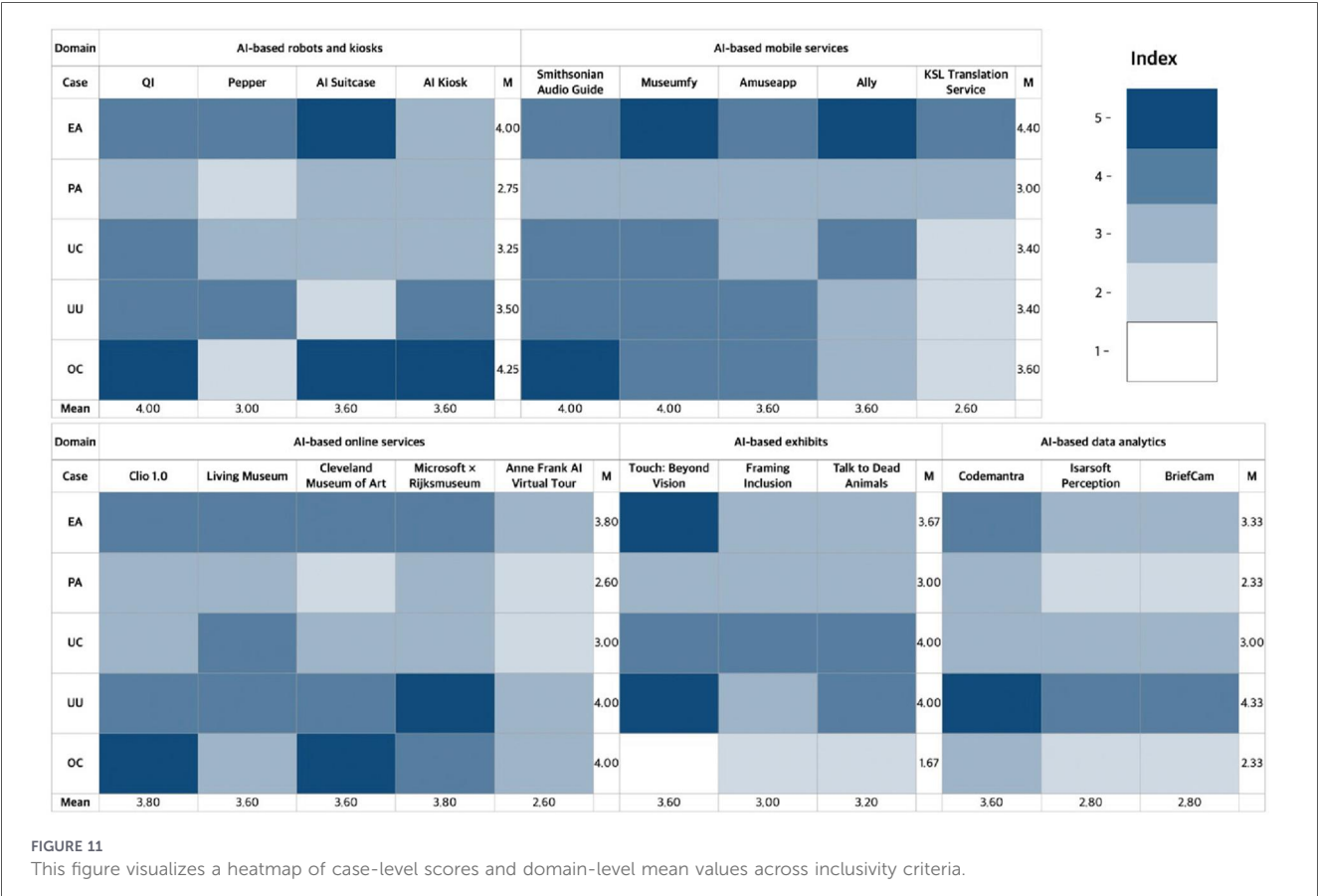


FIGURE 11 This figure visualizes a heatmap of case-level scores and domain-level mean values across inclusivity criteria.

based on scripted sequences, resulting in low levels of learning-based personalization, and limitations were identified with respect to broader inclusivity measures such as sign language, high-contrast modes, and braille.

3.2.2 AI-based mobile services

In the AI-based mobile services domain, Effortless Accessibility demonstrated the highest performance. At the same time, Personal Adaptivity recorded relatively low scores, consistent with the results in Section 3.1, which indicated generally low mean values for Personal Adaptivity. Mobile services effectively lower access barriers by allowing visitors to use their own familiar smart devices, enabling immediate access without requiring separate equipment rental or additional learning. Cases such as Museumfy and Ally contributed to lowering accessibility barriers by minimizing initial entry burdens through camera recognition, automatic translation, and intuitive interfaces. However, these services generally remained at a limited level of personalization, and adaptive interactions reflecting complex individual characteristics such as sensory sensitivity, cognitive levels, or mobility constraints were not sufficiently implemented. As a result, while accessibility was secured at a high level, repeated patterns were observed in which services did not develop into structures capable of providing personalized experiences. For instance, in the case of the KSL translation service, although automatic sign language translation services for visitors with hearing impairments were

provided, additional personalization functions were limited to on-screen text adjustments, and no options were offered to learn visitor characteristics or to automatically respond to additional visitor needs by providing tailored guidance.

3.2.3 AI-based online services

In the AI-based online services domain, Universal Usability and Operational Continuity demonstrated relatively high performance, whereas Personal Adaptivity received low evaluations, similar to the cases observed in the AI-based robots and kiosks and AI-based mobile services domains. Because web-based platforms and online guides do not directly depend on physical environments, maintenance is generally limited to software-level management and is therefore relatively undemanding. Moreover, social integration tends to be maintained more stably, as these services provide access environments that do not distinguish or segregate specific users. For example, the Rijksmuseum’s project with Microsoft used AI technologies to build large-scale, detailed online artwork explanations presented in text-based formats accessible to anyone through existing museum websites, and further expanded these explanations by incorporating descriptions of expressive techniques and textures, thereby enabling visually impaired users to experience artworks in online environments. This was evaluated positively in that elements previously accessible only to sighted users were extended to users with visual impairments. Such services maintain consistent interfaces

and information structures across diverse regions and access conditions, and with the exception of Living Museum, most cases were projects led by museums or related institutions, highlighting the potential for long-term operation regardless of external circumstances. However, these online services have structural limitations in precisely detecting real-time user behaviors or environmental contexts, and therefore, functions that adjust experiences according to individual characteristics remain limited. In the case of the Anne Frank AI Virtual Tour, while an AI avatar provides multilingual narration in virtual museum exploration, no personalization options were provided to adjust information according to visitors' sensory conditions, learning levels, or comprehension, and the lack of diversified auditory and visual assistive functions revealed limitations in actively addressing inclusivity issues. Accordingly, while online services demonstrate strengths in stability and universality, they exhibit structural limitations in terms of personalized interaction.

3.2.4 AI-based exhibits

In the AI-based exhibits domain, User Centeredness and Universal Usability were prominent, whereas Operational Continuity emerged as the most vulnerable criterion. In AI-based exhibitions, design patterns were repeatedly observed in which technology is positioned as a supportive element, with visitor participation and interpretation placed at the center of the experience. For example, in "Talk to Dead Animals," visitors' questions and choices drive the progression of interactions, and in "Framing Inclusion," participants with disabilities assume the role of creative agents who use AI as a tool. These characteristics contribute to strengthening user agency and experiential openness by positioning AI as a supportive and trustworthy tool for exhibition viewing and participation. However, most exhibition-based AI systems are operated only for the duration of specific exhibitions or projects, and after exhibitions end, they remain only as fragmented materials or archives. For instance, "Touch: Beyond Vision" was evaluated as a case that provided high social significance and positive visitor experiences, but it was operated as a single-day project, revealing limitations in securing sustained accessibility. This differs from the way in which works that are evaluated as meaningful and valuable typically achieve continued exposure and form social discourse through repeated exhibitions.

3.2.5 AI-based data analytics

In the AI-based data analytics domain, Universal Usability received relatively high evaluations, whereas Personal Adaptivity and Operational Continuity showed low performance. Data analytics-based AI operates invisibly in the back end of exhibition environments without being directly exposed to visitors, thereby possessing non-visible characteristics that do not reveal or segregate specific users. Cases such as CodeMantra contribute to providing equal and non-discriminatory access environments for all users and visitors by automatically generating digital content that complies with accessibility standards from analog documents held by museums. However, for the outcomes of such AI-based data analytics to be translated into actual service improvements or personalized

experiences, additional human intervention and organizational decision-making processes are required, as seen in cases such as Isarsoft Perception and BriefCam. As a result, these systems can only present indirect and macro-level perspectives, and therefore fail to guarantee direct inclusivity at the level of individual visitors. Furthermore, as observed across cases, data analytics projects are typically commissioned by museums to external organizations or companies and conducted based on agreements and project-based collaborations, revealing structural constraints that make it difficult to achieve consistent performance in terms of long-term operation.

4 Discussion

The five criteria derived in this study are conceptually continuous with the Principles of Inclusive Design proposed by the [Design Council \(2006\)](#), while being reconfigured in a way that expands the domains that must be considered within AI-mediated interaction environments in museums. Through abductive analysis of the relationships between the existing principles and the aspects revealed in each case, it was found that the original principles were primarily established around physical environments, usability, and the provision of diverse choices. However, the case analyses in this study indicate that, as AI-based systems intervene as agents that mediate and regulate visitors' experiences, not only accessibility and personalization but also user agency, social integration, and operational continuity must be considered, confirming that a more complex and integrated approach to inclusivity is required.

Before the main discussion, it is important to clarify that elements not addressed within the proposed framework, such as humanities-based museum practices, curatorial interpretation, governance, and ethical judgment, should not be excluded from considerations of inclusive AI. As noted above, these dimensions are essential to inclusive AI applications, but they fall outside the scope of this study, which focuses on the design-level of AI applications. Accordingly, the five criteria were intended and applied not as definitive indicators of inclusivity, but as practical checkpoints for reflection and evaluation.

First, from the perspective of Effortless Accessibility, when AI technologies are applied to expand inclusivity in museum environments, a shift is required from physical and product-centered accessibility to interaction-centered accessibility. This implies that, beyond physical access to museum services, interface configuration, information delivery, and interaction procedures must be carefully considered. Mobile services and online platforms increased accessibility by providing inclusive interfaces and functions through devices that visitors are already familiar with, without requiring additional equipment. In this sense, most cases were found to focus on reducing visitors' usage burden through appropriate interaction design. This suggests that product and space-centered accessibility is insufficient to explain the cognitive burdens that arise during interaction with AI-based inclusive services, and that in AI-mediated environments, interaction structures themselves become a core component of accessibility. This interpretation is supported by recent museum user research, which suggests that visitors are more likely to engage with digital services when they

are delivered through familiar personal devices and low-burden access formats (Mazzanti et al., 2025, pp. 4–6, 9–10). Therefore, how interaction along with physical accessibility is experienced by users in practice must be taken into consideration to achieve Effortless Accessibility in AI-mediated museum inclusivity.

Second, from the perspective of Personal Adaptivity, the analysis suggests that it is important to go beyond offering multiple options to visitors and to respond to their needs by recognizing the contexts in which they are situated. Previous research coherently noted that preferences for AI-mediated museum guidance vary depending on the context, so that adaptive support should not be in the condition of offering limited options (Chen et al., 2025, p. 1). Another research on personalized digital collections also suggested that personalized recommendation is linked with deeper engagement, and should be evaluated in terms of how it shapes actual engagement with users in use going beyond offering the options (Hughes-Noehrer et al., 2025, p. 20). However, while some cases provided basic personalization functions such as language selection and text adjustment, these were mostly limited to options that users had to configure manually. This shows that the existing principles' emphasis on "recognizing diversity and difference," "offering choices," and "flexibility in use" is still being implemented in static ways in AI-based inclusive technologies in museums, indicating substantial room for improvement through technological capabilities. These limitations are closely linked to complex issues such as data ethics, legal risks, and increased system complexity which have also been identified as constraints on the implementation of personalized systems in a smart museum environment study (Ivanov and Velkova, 2025, pp. 35–36). Therefore, AI-based inclusive services and products require not only more proactive and adaptive design approaches that leverage technological characteristics to recognize and reflect visitors' sensory sensitivity, comprehension levels, and mobility conditions in real time, but also changes at the level of operational strategy.

Third, User Centeredness corresponds to the principle "Places People at the Heart of the Design Process" among the existing principles. While the original principle emphasizes deeply considering users in the design process, this criterion implies that the issue should be extended to the operational stage, specifically to the question of who holds agency over the experience. As one of the most representative advanced technologies, AI itself can become a major component shaping viewing experiences. In many AI-based inclusive cases, technology was observed to go beyond a supportive role and to structure viewing flows and determine the sequence of information provision, thereby partially limiting visitors' ranges of choice. However, when AI is not the objective, it must function as a supportive driver of visitors' questions, choices, and creative activities, delegating agency to the visitors. According to the research on the AI Suitcase and its development process, the user-based study also showed that autonomy in museum interaction was considered and applied as an important condition of actual experience. The result also showed that blind visitors valued being able to choose exhibits according to their own interests and move at their own pace (Kayukawa et al., 2023, pp. 2, 8–9). Research on audio guide further identified that users' intentional operation and control

play an important role in building trust in AI-mediated experiences (Saito and Yamada, 2024, pp. 48–49). Therefore, from the perspective of inclusive use of AI technologies in museums, User Centeredness suggests that it is necessary to provide visitors with the greatest possible agency and flexibility during actual use.

Fourth, from the perspective of Universal Usability, it was emphasized that integrating visitors with diverse characteristics and backgrounds and designing non-stigmatizing viewing experiences must be considered. In line with the argument that accessibility support may become stigmatizing when it marks blind visitors as socially distinct within a shared art viewing experience (Li et al., 2023, p. 10), case analysis showed that when AI-based support that expands accessibility is provided in the form of separate devices or services for specific groups, it can make users visually identifiable and induce socially segregated experiences. For example, although AI Suitcase was evaluated as having high functional inclusivity effects, it was pointed out that visually impaired visitors carrying relatively large equipment during their visits may be exposed to the risk of stigma. This suggests that when AI technologies are deployed for inclusivity, Universal Usability should be designed more seamlessly and sensitively so that a wide range of visitors can share the same experience structure.

Finally, Operational Continuity emphasizes the need to reconceptualize inclusivity not as a design attribute but as an operational outcome. The continuity of digital initiatives, including AI, can be achieved based on strategic, infrastructural, and organizational conditions, including maintenance, upgrades, staff training, capacity, and governance. Without these conditions, digital applications are often discontinued (Nikolaou, 2024, pp. 1,789–1,791; Han, 2026, p. 7). Reflecting this, domain-level comparisons showed that robots and kiosks operated as permanent installations demonstrated high operational continuity based on stable maintenance systems, whereas AI-based exhibitions and data analytics were often limited to short-term contractual projects or pilot operations, resulting in outcomes that were not sustained in the long term. Therefore, for AI technologies to effectively achieve inclusivity, it is necessary to secure operational continuity and systems that allow strategies and outcomes to be evaluated from a long-term perspective, beyond the fact that they were designed for inclusivity. This suggests that, unlike existing discussions that have focused mainly on the presence of functions and design intentions, AI-based inclusivity requires attention to maintenance, updates, and governance structures as well.

In summary, the five criteria identified in this study inherit the core philosophy of the Principles of Inclusive Design (Design Council, 2006) while expanding inclusivity into a dynamic concept by integrating issues of interaction structures, data-driven context recognition, agency, social stigma, and operational continuity that arise when AI technologies mediate viewing experiences. In addition, the preceding domain-based analysis showed that AI-based inclusivity implementation forms different strengths and limitations depending on the type of technology. These results raise the need to discuss what kinds of design and operational strategies each domain assumes in implementing inclusivity, and what conditions must be supplemented in the future for more sustainable and substantial

inclusivity to be realized. Based on this need, the following points are discussed.

First, AI-based robots and kiosks are generally operated as permanent or long-term installations with high costs invested and stable maintenance systems, which gives them strengths from a long-term operational perspective, but conversely acts as a constraint on the expansion of personalization functions. Previous research has also pointed to this issue as museum kiosk study argued that fixed museum interactives should support different visitor paths according to their interests and plan, as well as provide information at different levels while integrated into the context (Burmistrov, 2015, pp. 4–5). Also, while recent museum robot research addressing the fact that highly individualized personalization is often difficult in public cultural venues, they suggested that immediately interpretable cues remain feasible for personalization (Yoon et al., 2025, pp. 1–4, 25), stating that personalization is an achievable goal through light and adaptive technologies. Therefore, when introducing AI-based inclusive technologies in this domain, considerations should be included in advance that allow interactions to be adjusted based on visitors' characteristics in response to future needs while maintaining operational stability. For example, it is necessary to secure functional and interface extensibility at the initial design stage, such as module-level personalization structures for future possible adoptions.

AI-based mobile services can lower access barriers by utilizing visitors' familiar personal devices (Roussou and Katifori, 2018, p. 2), thus become strategies that can be rapidly and effectively distributed. However, as it has been pointed out that securing accessibility does not automatically provide personalized experiences, when introducing mobile services, designs should go beyond convenience-oriented functions and actively incorporate ways to understand and reflect visitors' states and contexts through various sensors. If complex visitor characteristics such as sensory sensitivity, cognitive load, and mobility constraints are not reflected, mobile services may ultimately fail to provide appropriate support for all, even though they may be accessible for all. Therefore, to strengthen inclusivity in this domain, strategies are required to incorporate visitor profiling and context-awareness functions into the initial approach, while also considering ethical, legal, and system-load issues mentioned earlier.

In the case of AI-based online services, they are advantageous for securing non-stigmatizing operations and stability because physical environmental constraints are removed, and updates and maintenance are limited to software. However, because it is difficult to sufficiently grasp users' actual sensory environments and cognitive states, there are structural limitations in adjusting experiences to individual characteristics. Therefore, both diversification of information delivery methods and AI's understanding of visitors should be designed in an integrated manner. For example, texts and images displayed online should not follow a single explanation format but should be systematically structured with adjustable amounts of content, levels of difficulty, and sensory substitution information so that users can have experiences suited to their own situations. Recent research on remote virtual museum access for people with visual impairments depicted that the experiences were strengthened when information is organized and delivered through multiple descriptive layers including sensory, emotional, historical, and

structural cues (Yücel and Rızvanoğlu, 2025, pp. 1, 5). In other words, if real-time recognition and adaptation through websites are difficult, inclusivity strategies should be supplemented by designing multiple layers of selectable experiences.

Fourth, AI-based exhibits can realize high user agency and social inclusivity through structures that place visitor participation and interpretation at the center, and visitor agency and collaborative participation were also emphasized for meaningful engagement in previous research on AI-related exhibits (Long et al., 2021, pp. 2, 5–6). But they have structural limitations in that they are mostly operated only for short-term projects or limited exhibition periods. Therefore, to expand the inclusivity effects of AI-based exhibitions, it is recommended to design structures that allow access even after exhibitions end, such as archiving content on online platforms or linking with permanent programs. In addition, if continuity cannot be secured due to the nature of exhibitions, they may relate to educational programs and local community workshops so that inclusive experiences can spread widely and sustainably. This suggestion corresponds to the results of a prior study showing that AI-based exhibition formats developed collaborative learning activities designed for broader educational settings in community-based contexts (Candello et al., 2021, pp. 41–44).

Finally, AI-based data analytics has the advantage of expanding inclusivity without social stigma because it can improve inclusivity across the entire museum environment without distinctive segregation of specific visitors. However, if analysis results do not lead to actual changes, they become ineffective. Previous studies also mentioned that analytics should be linked to iterative processes and operational decisions for comfort, safety, and attractiveness perceived by visitors (Ceccarelli et al., 2024, pp. 2, 4; Centorrino et al., 2021, pp. 8, 14). Therefore, when introducing technologies in this domain, organizational processes that clearly connect analysis stages to the implementation of improvements must be established. In addition, since such systems are generally operated through contracts with external companies that possess specialized technologies, mechanisms are required either to gradually internalize data utilization capabilities within institutions or to secure long-term contractual arrangements. Moreover, existing group-oriented functions such as visitor counting, spatial congestion analysis, and risk situation detection should be further advanced using computer vision-based AI so that they can be connected to personalized experiences.

5 Conclusion

This study aimed to derive and validate criteria for how AI technologies should be applied in museum environments to secure inclusivity. It also examined how AI-based technologies contribute to inclusivity in museums and in what ways their effects are strengthened or constrained. To this end, the study categorized current AI services and products in museums into five domains: AI-based robots and kiosks, mobile services, online services, exhibits, and data analytics, and conducted qualitative and quantitative analyses of a total of 20 cases related to inclusivity across these domains.

The first step was to derive five criteria through an abductive approach. This process incorporated a deductive perspective

grounded in the Principles of Inclusive Design proposed by the [Design Council \(2006\)](#), while simultaneously employing inductive interpretation based on the characteristics, strengths, and limitations observed in each case. The inference and criteria development process was not linear but was conducted iteratively until theoretical saturation was reached. Through this process, five criteria were established, namely Effortless Accessibility, Personal Adaptivity, User Centeredness, Universal Usability, and Operational Continuity. These criteria are conceptually continuous with existing principles, while also forming an expanded framework that reflects conditions emerging in museum environments where AI technologies are employed to enhance inclusivity.

Subsequently, 20 AI-based cases used to enhance inclusivity in museums were classified into the five domains and analyzed based on the derived criteria. Both qualitative and quantitative analyses were conducted to verify the validity of the criteria. The results of the criteria-centered analysis indicated that AI-based inclusivity in museums requires a systematic approach that integrates interaction structures, context-aware adaptivity, user agency, social integration, and operational strategies, and that the five derived criteria collectively encompass these elements.

The domain-based analysis further indicated that the strengths and limitations of inclusive implementation vary structurally across AI technology domains, suggesting that differentiated adoption strategies are required. For AI-based robots and kiosks, it is necessary to secure the expandability of interfaces and functions at the initial design stage. From the same perspective, mobile services also require context-aware design to enable personalized adaptation. Meanwhile, as online services operate on web-based structures and are therefore limited in real-time personalization, strategies that provide selectable experiences through multi-layered information structures are required. In the case of AI-based exhibits, dissemination plans and structures that allow access even after the exhibition period are needed. For data analytics-based AI, it was found that linkage with organizational execution systems is essential for analytical results to translate into actual inclusive change.

The standardized analysis table used in this study enables systematic content analysis and cross-case comparison, and thus can function as a reusable qualitative and quantitative framework. Moreover, this analytical method can serve as a professional tool that provides practical guidelines and critical checkpoints for visitors, museum professionals, inclusivity experts, designers, and policy makers, and can also be applied to cultural institutions and public facilities beyond museums. For example, the table allows stakeholders to qualitatively review and evaluate AI-based inclusive services or products that are planned for adoption or already in operation, while also enabling quantitative analysis that supports relative comparisons across criteria and between similar technologies. Ultimately, this combined analytical approach provides important criteria for applying AI technologies in expanding inclusivity in museum environments and contributes to enhancing the qualitative value and performance of services and products by considering multiple dimensions, even when structural limitations make it difficult to satisfy all criteria simultaneously within a given domain. Taken together, the findings underscore that AI should not be adopted in museums as a presumed solution or magic

wand for inclusivity, but rather implemented through careful evaluation, validation, and deliberation regarding its social and experiential consequences.

Despite these contributions, this study has several limitations that should be addressed through future research. First, although the 20 cases used in this study were selected to cover diverse domains of AI application in museums, they have limited statistical representativeness. Therefore, the proposed framework and findings should be understood as analytical indicators for practical interpretation, rather than generalized statistically or interpreted as evidence of causal effects. Future research should expand the case pool and examine whether the proposed criteria remain applicable across broader contexts.

Another limitation concerns the scoring process. The scores were based on documented cases and consensus-based researcher assessments, without drawing on visitor-based data or experimental evidence. Since inclusive is strongly shaped by visitors' subjective perceptions, a high evaluation score does not necessarily mean that visitors perceive the experience as inclusive. Therefore, future research should retain score-based and criterion-based evaluation while involving a larger group of coders and incorporating analyses of visitors' perceptions and responses in order to examine the relationship between criterion fulfillment and perceived inclusivity.

Third, inclusivity in AI-mediated museum environments may be understood more broadly than the present framework. For example, previous research suggests that AI may privilege dominant interpretations while marginalizing minority or culturally specific viewpoints, and that AI in cultural heritage requires sector-specific ethical guidance ([Tiribelli et al., 2024](#), pp. 294, 299). This indicates that inclusivity may encompass broader dimensions such as ethical governance. Accordingly, future research may extend the present design-centered framework by examining broader dimensions related to the use of AI in museums.

Finally, the proposed framework assumes the possibility of periodic recalibration. AI technologies and museum operating conditions evolve rapidly, and the meaning of inclusive AI may also change as these conditions shift. Consequently, this framework may be periodically updated through new cases and visitor-centered empirical analyses, while longitudinal research should examine the temporal stability of the framework and how the applicability of its criteria changes over time.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#), further inquiries can be directed to the corresponding author.

Author contributions

SH: Resources, Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Methodology, Conceptualization, Data curation, Investigation. EH: Supervision, Data curation, Investigation, Writing – review & editing, Resources, Validation. H-KL: Methodology, Validation, Supervision,

Investigation, Formal analysis, Conceptualization, Project administration, Writing – review & editing, Funding acquisition.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. The authors verify and take full responsibility for the use of generative AI in the preparation of this manuscript. Generative AI was used to check grammar and improve the clarity and coherence of the language. Prompts

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fhumd.2026.1799182/full#supplementary-material>

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