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A systematic review of digital transformation technologies in museum exhibition

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ABSTRACT

Museum exhibitions, both temporary and permanent, form an essential link between a society and its cultural, historical, and artistic heritage sites. Curating artifacts and thematic displays in museum exhibitions can promote dialogue, foster cultural appreciation, and contribute to heritage preservation. The traditional way of holding museum exhibitions, heavily reliant on the expertise of designers and curatorial staff, makes them a labor-intensive process, from conceptualization to visitor engagement analysis. This review systematically compiles and examines how the application of digital transformation technologies (DTTs) has revolutionized museum exhibitions and augmented their future potential. DTTs such as artificial intelligence, immersive technologies, additive manufacturing, the Internet of Things, and cloud computing can help create engaging designs, improve accessibility and inclusivity, enhance educational potential, and allow for sophisticated visitor experience data collection and analyses, improving exhibit management. However, despite multiple specialized studies on DTTs and their roles in museum exhibitions, the connections between technology and application scenarios remain underexplored. By addressing this gap, this study is expected to inform and inspire practitioners in the museum and heritage sectors and present new research avenues for scholars.

1. Introduction

Digital transformation in museums is an emerging field that applies computer technology and scientific methods to the preservation, curation, display, and dissemination of historical artifacts and art collections, as well as to the production of artwork (Marty & Jones, 2008; Srinivasan, Boast, Furner, & Becvar, 2009). In the information age, museums have been undergoing a digital transformation to enhance the visitor experience, open access to collections, increase research opportunities, and preserve knowledge as physical assets are threatened or require a high level of security (Bertacchini & Morando, 2013; Guarino, Di Palma, Menini, & Gallo, 2020; Liao, Zhao, & Sun, 2020; Vaz, Fernandes, & Veiga, 2018b). The use of digital technology in museums dates back to the 1950s with the debut of Ben Laposky's Oscillons. Since then, the use of computers and information technology in museum digitization has boomed, expanding to numerous digital transformation technologies (DTTs) such as artificial intelligence (AI), immersion technology, additive manufacturing (AM), the Internet of Things (IoT), and cloud computing (Fig. 1) (Carrozzino & Bergamasco, 2010; Kounavis, Kasimati, & Zamani, 2012; Merritt, 2017).

The COVID-19 pandemic led to worldwide lockdowns in varying degrees (Mucci, Mucci, & Diolaiuti, 2020; Onyeaka, Anumudu, Al-Sharify, Egele-Godswill, & Mbaegbu, 2021). The only way museums could remain open during this time was by going digital (Markopoulos, Ye, Markopoulos, & Luimula, 2021; Meng, Chu, & Chiu, 2023; Noehrer, Gilmore, Jay, & Yehudi, 2021), which increased the popularity of digital museums (Agostino, Arnaboldi, & Lampis, 2020; Burke, Jørgensen, & Jørgensen, 2020; Giannini & Bowen, 2022; King, Smith, Wilson, & Williams, 2021; Samaroudi, Echavarria, & Perry, 2020; Tan & Tan, 2021). Subsequently, the pandemic catalyzed the rapid adoption of DTTs in the museum industry, prompting them to explore innovative ways of engaging audiences remotely. In 2020, the International Council of Museums (ICOM) undertook a survey across 107 countries, with approximately 1,600 responses, and found that approximately 95% of museums were closed due to the pandemic (International Council of Museums, 2020). By contrast, the ICOM 2021 report revealed a notable increase of 5.6% in the digital activities of museums and an increase of 6.5% in the number of museums and galleries planning to start exhibiting online (International Council of Museums, 2021).

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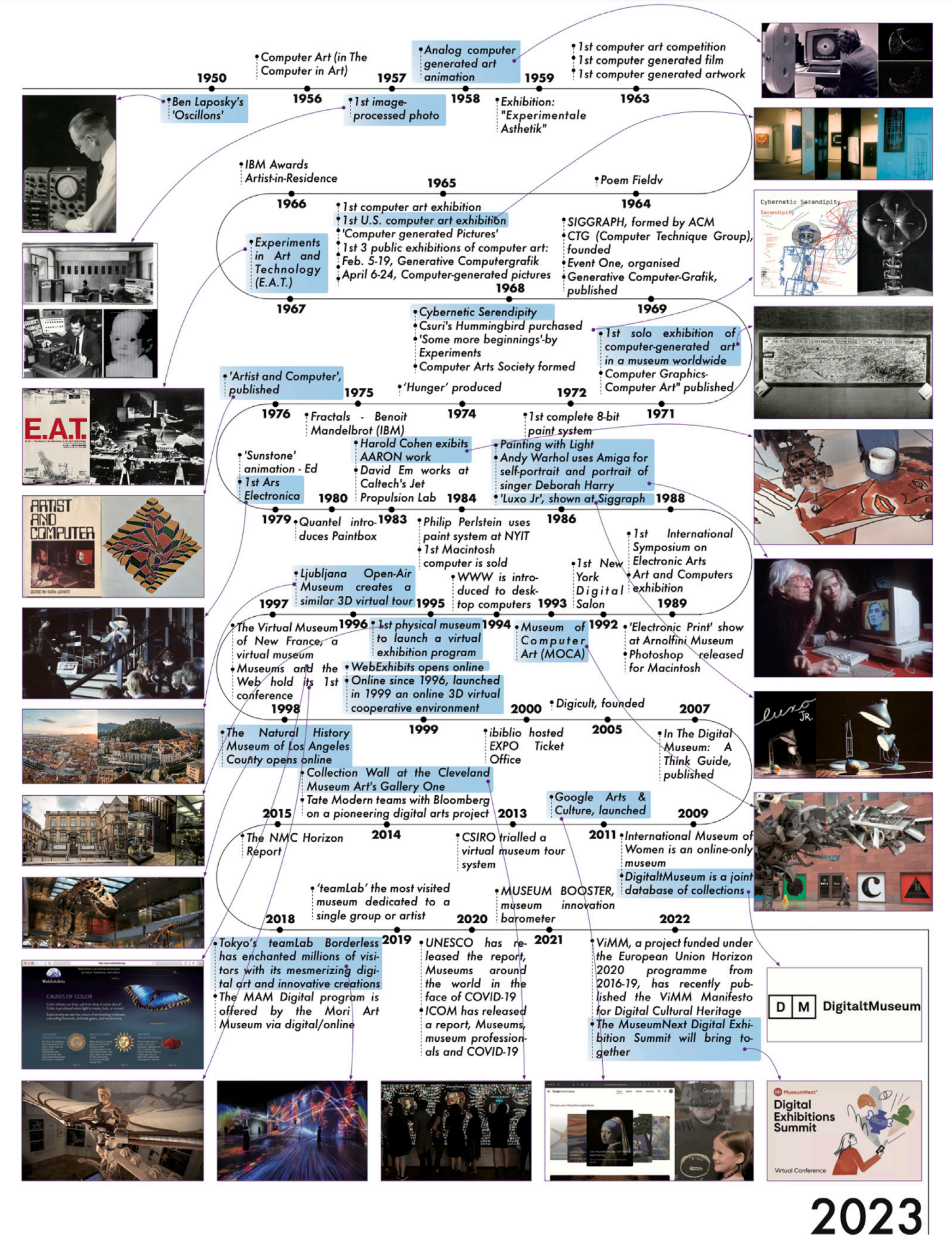

Fig. 1. Timeline of museum digital transformation.

The 2021 Museum Innovation Barometer provides valuable insights into the impact of the pandemic on the digital transformation of museums (Booster, 2021). This shift should be seen as an opportunity for cultural institutions to strike a harmonious balance between physical and digital experiences, enhance accessibility, and reach wider audiences while maintaining the authenticity and richness of in-person exhibits.

While previous studies have substantiated the increasing prevalence of DTTs in museums, recent research has highlighted their significant role in museum exhibitions. DTTs actively reshape museum experiences by offering novel avenues for creation, engagement, education, and accessibility. In particular, ChatGPT, an AI-powered chatbot released by OpenAI in 2022, has become a worldwide phenomenon, arguably altering human–computer interaction (Wu et al., 2023). During the first few weeks of its initial release, it attracted over one million users who tested it and gave a mixture of impressive, nonsensical, and useful responses to any question or comment, being able to offer basic software code, chat-based customer service, summaries of scientific papers, and emotionally personalized advice, among other things. Next, the announcement of the release of Apple Vision Pro, a mixed reality (MR) headset, at the 2023 Worldwide Developers Conference recalled the era of spatial computing as it can blend digital content with physical space. Vision Pro can transform how users use apps they love by using motion gestures, eye tracking, and voice input to interact with the headset. Moreover, additive manufacturing (AM) and 3D scanning have attracted increasing interest because they are potential solutions to enabling Cathedral Notre Dame de Paris to rise from the ashes, literally, as it was destroyed by a fire in 2019. The rebuilding has been a challenge, but fortunately, architectural historian Dr. Andrew Tallon has been scanning the entire cathedral structure in 3D since

2015, creating an accurate digital replica that can be used to 3D print the destroyed parts (Mouaddib, Pamart, Pierrot-Deseilligny, & Girardeau-Montaut, 2023; Sandron & Tallon, 2020).

These new DTTs emphasize the ongoing significance of digital innovation not only in our daily lives but also in the museum exhibition sector. However, a comprehensive and systematic review of DTTs in museum exhibitions is lacking; subsequently, a perspective on how state-of-the-art DTTs can revolutionize museum exhibitions. Therefore, in this review, we comprehensively examine the application of these technologies in museum exhibitions catering to newcomers and experts. By integrating insights from the fields of DTTs and museum studies, this review provides a thorough understanding of the subject matter and extends previous literature on the application of digital technologies in museums. While prior reviews have focused on specific technologies, such as augmented reality (AR), virtual reality (VR), and 3D printing, or specific aspects of the museum experience, this article provides a more comprehensive and integrated analysis of the various DTTs and their impacts across multiple dimensions of museum exhibitions. By synthesizing insights from a diverse range of studies and case examples, this review offers a holistic understanding of how DTTs are transforming the design, delivery, and evaluation of museum experiences in the digital age.

We conducted a state-of-the-art review of DTTs in museum exhibitions. We also employed a comprehensive literature collection and analysis process focusing on the application and impact of DTTs in museum exhibitions. We searched the major electronic databases, such as Nature Portfolio, American Association for the Advancement of Science, Scopus, Web of Science, ACM Digital Library, and IEEE Xplore. The search strategy involved using a combination of keywords related to DTTs (e.g., "artificial intelligence," "virtual reality," "3D printing," "Internet of Things") and museum contexts (e.g., "museum," "exhibition," "visitor experience"). The inclusion criteria were: (1) peer-reviewed articles published between 2010 and 2023; (2) articles focusing on the application of DTTs in museum exhibitions; and (3) articles providing empirical evidence, case studies, or theoretical insights into the impact of DTTs on visitor engagement, accessibility, education, or exhibition management. The selected articles underwent a rigorous two-stage screening process involving title and abstract review, followed by full-text examination.

The remainder of the paper is structured as follows: Section 2 provides an overview of key DTTs; Section 3 explores their applications in designing engaging exhibitions, enhancing accessibility and inclusion, improving educational potential, managing visitor experiences, and facilitating exhibit management; Section 4 discusses the challenges and future research directions; and Section 5 concludes the paper by summarizing the findings and implications for the museum sector.

2. Digital transformation technologies: An overview

2.1. *Artificial intelligence*

AI is an emerging field of technology with the potential to revolutionize how we live and work (Ghahramani, 2015; Glover, 1986; Haugeland, 1989; Minsky, 1961; Russell, 2010) The concept of AI is that machines can be programmed to think like humans and make decisions based on collected data. There are several AI subspecialties with unique properties for different purposes in museum exhibitions, including machine learning (ML), natural language processing (NLP), computer vision, robotics, and recommendation systems (Fig. 2).

2.1.1. *Machine learning*

ML is a branch of AI that enables computers to learn from data without explicit programming (Jordan & Mitchell, 2015; Mitchell et al., 2007; Sammut & Webb, 2011). It focuses on developing algorithms and models that can learn from data and make predictions, covering a wide variety of applications in image recognition, NLP, and autonomous driving (Collobert et al., 2011; Dosovitskiy et al., 2020; Levinson et al., 2011). ML uses artificial neural networks (ANNs), which are computer systems inspired by how the human brain processes information (Levinson et al., 2011). An ANN comprises connected artificial neurons that mimic neurons in the human brain. Deep learning uses multiple ANNs to alleviate traditional time-consuming feature extraction (Goodfellow, Bengio, & Courville, 2016; LeCun, Bengio, & Hinton, 2015; Yegnanarayana, 2009; Zheng, Zhang, Chen, & Watanabe, 2023). The term deep is named after the ANN architecture, which comprises input, output, and multiple hidden layers. ML can be used for prediction and generation depending on the input and output data. For instance, ML algorithms can be used to identify patterns in data and make predictions, such as predicting visitor behavior by analyzing visitor data. More complex generation tasks, such as artwork generation, can be achieved using deep generative networks.

There are three ML frameworks: supervised, unsupervised, and reinforcement learning (Fig. 3). In supervised learning, a machine is trained to make predictions using labeled data. Labels are data points preassigned by humans (Caruana & Niculescu-Mizil, 2006). The machine was given a set of labeled data and a set of algorithms to make predictions.

Supervised learning is useful for tasks such as classification, where a machine is given and asked to classify data. Supervised learning is mainly used for classification and regression problems (Kotsiantis et al., 2007), such as predicting the class or category of artwork and visitors' ratings of artworks or museums (Cheng & Bernstein, 2015; Lecoutre, Negrevergne, & Yger, 2017; Lu, Lin, Jin, Yang, & Wang, 2014; Portugal, Alencar, & Cowan, 2018). In unsupervised learning, a machine is trained to make predictions without labels (Barlow, 1989). Instead, the machine is provided with a set of unlabeled data and a set of algorithms to make predictions. Unsupervised learning is useful for tasks such as generation and clustering, where a machine is given data and asked to identify groups or relationships between data points (Hastie et al., 2001; Taigman, Polyak, & Wolf, 2016). Typical unsupervised learning models include variational autoencoders (VAE) and generative adversarial networks (GAN) (Goodfellow et al., 2020; Kingma et al., 2019; Zheng, Chen, Guo, Samitsu, & Watanabe, 2021; Zheng, Chen, Jiang, Naito, & Watanabe, 2023). In reinforcement learning, a machine is trained to make decisions by being rewarded for successful actions and punished for failed ones (Kaelbling, Littman, & Moore, 1996; Sutton & Barto, 2018). It can be applied to museum exhibitions and communication domains, such as creating paintings and visual arts, storytelling, and designing interactive games (Xie, Zhao, Tian, Zhang, & Sugiyam, 2015). Reinforcement learning can be a powerful tool for artists and creative professionals to generate new and innovative artworks. Through trial and error, reinforcement learning can help artists explore new creative possibilities and push the boundaries of their respective fields.

Semi-supervised learning, a combination of supervised and unsupervised learning, utilizes a small amount of labeled data with a large amount of unlabeled data. Popular semi-supervised learning uses a large language model (LLM) trained to understand and generate text in a human-like fashion. Many state-of-the-art LLMs are based on transformers that harness attention mechanisms to better understand the context of a word (Vaswani et al., 2017). LLMs learn from vast amounts of text containing trillions of tokens (i.e., sequences of words) from the Internet using a massively parallel processing approach. During training, the transformer model executes each token's embeddings into a context vector. This enables them to produce coherent and contextually appropriate responses when presented with a prompt or query. Typical LLMs include Metas LLaMA, released in February 2023 (Touvron et al., 2023), OpenAIs GPT-4, released in March 2023 (OpenAI, 2023), and Google's PaLM 2 in May 2023 (Anil et al., 2023). Owing to advances in LLMs and deep generative models, text-based-generative models have been developed to generate detailed images (e.g., stable diffusion from stable AI (Rombach, Blattmann, Lorenz, Esser, & Ommer, 2021)) and 3D objects (Zheng, Watanabe, Paik, et al., 2024) conditioned on text descriptions.

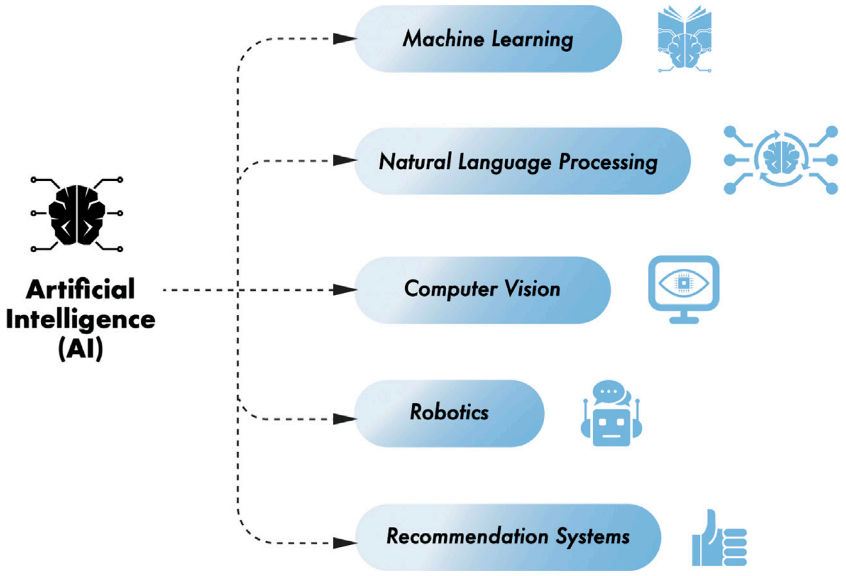

Fig. 2. Classification of Artificial Intelligence.

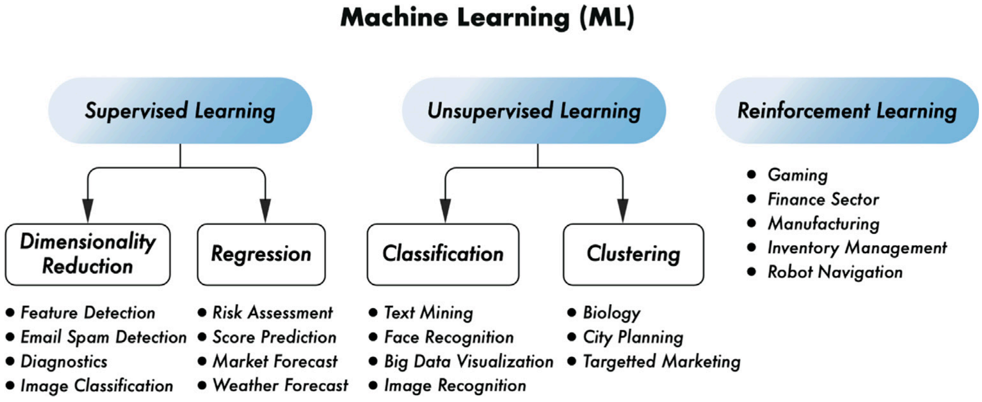

Fig. 3. Classification of machine learning and its applications in museum exhibitions.

2.1.2. Natural language processing

NLP addresses the interaction between computers and human languages (Bird, Klein, & Loper, 2009; Hirschberg & Manning, 2015; Manning & Schutze, 1999; Onishi, Kadohira, & Watanabe, 2018; Young, Hazarika, Poria, & Cambria, 2018) by developing algorithms and models that enable computers to process, understand, and generate natural language data, such as text and speech. It combines computer science, linguistics, mathematics, and statistics techniques, such as ML, deep learning, statistical modeling, and rule-based approaches, to enable machines to understand human language. These techniques enable machines to learn from large amounts of data and use the learning to make predictions. Regarding museum exhibitions, NLP can be used for speech recognition, machine translation, virtual agents and chatbots, social media sentiment analysis, and text summarization (Fig. 4).

Speech recognition is the process of converting spoken language into text (Abdel-Hamid, Mohamed, Jiang, Deng, Penn, & Yu, 2014). This technology allows computers to transcribe and understand human speech, making it easier for people to interact using voice commands or dictation. Machine translation focuses on using computer algorithms to automatically translate text or speech from one language to another (He et al., 2016). The goal of machine translation is to enable communication between people who speak different languages without the need for human translators. A virtual agent is a software program that interacts with humans using natural language, typically in the form of text or speech (De Freitas, Gelaim, De Mello, & Silveira, 2019). These agents are often designed to perform specific tasks, such as answering customer service inquiries or providing technical support. By contrast, a chatbot is a type of virtual agent specifically designed to interact with humans through text-based conversations. Chatbots are often used to automate customer service interactions or provide information on demand Adamopoulou and Moussiades (2020), De Freitas et al. (2019), Thorp (2023). Chatbots such as ChatGPT can be programmed to handle a wide range of inquiries, from simple FAQ-style questions to more complex interactions that require a deeper understanding of user needs (OpenAI, 2023; Wu et al., 2023). Social media sentiment analysis refers to the process of using NLP techniques to extract and analyze sentiments or emotions expressed in social media content, such as tweets, blog posts, and comments (Hutto & Gilbert, 2014). Its goal is to identify the polarity of a piece of text, that is, whether it expresses a positive, negative, or neutral sentiment. Text summarization (Erkan & Radev, 2004; Nallapati et al., 2016) is the process of automatically generating a condensed version of a longer piece of text while preserving the most important information and meaning; the goal is to reduce the amount of text that must be read or processed while retaining key ideas and concepts.

2.1.3. Computer vision

Computer vision enables the interpretation and understanding of the visual world (Forsyth & Ponce, 2002; Voulodimos et al., 2018; Xu et al., 2021) to enable computers to see and make sense of digital images and

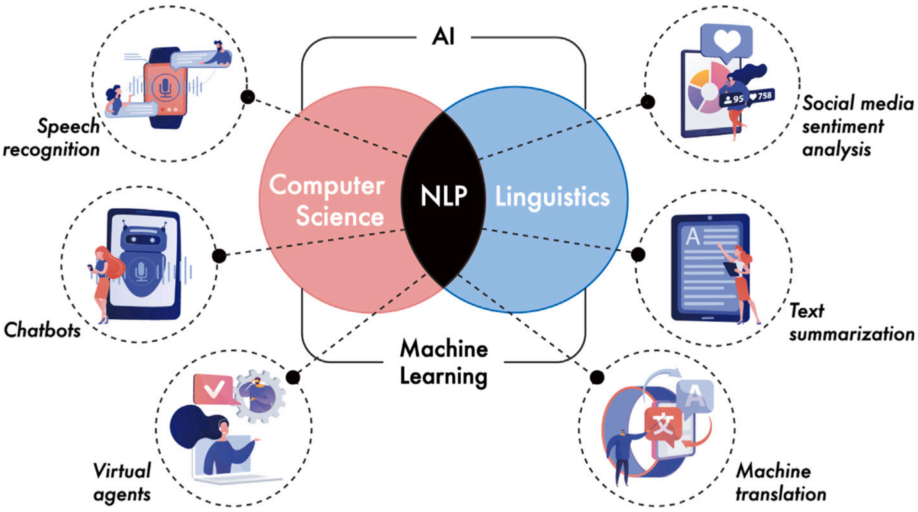

Fig. 4. Natural language processing in museum exhibitions.

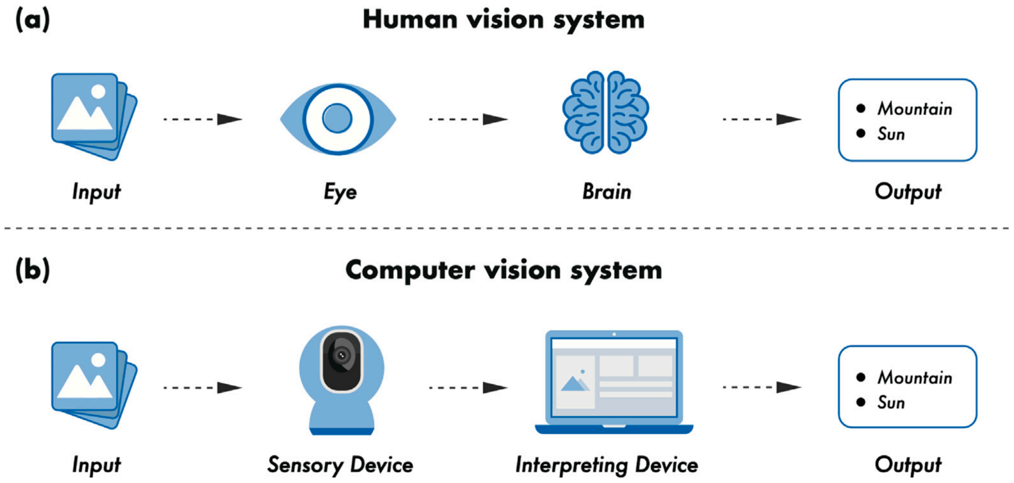

Fig. 5. Computer vision versus human vision.

videos in much the same way humans do, compared to human vision (see Fig. 5). It involves developing and applying various algorithms, mathematical models, and machine-learning techniques to analyze and understand digital images and videos. Key tasks that computer vision algorithms can perform include image classification, object detection and recognition, image segmentation, motion detection, and 3D scene reconstruction (Fig. 6).

Computer vision has become an increasingly important tool in designing and implementing museum exhibitions and communications. In exhibitions, it can enhance visitors' experiences in various ways. For example, it can create interactive exhibits that respond to visitor movements and actions or provide personalized recommendations and information based on visitor interests and preferences (Li, Zheng, Lu, Xanat, & Ochiai, 2022; Weinland, Ronfard, & Boyer, 2011) and immersive experiences that allow visitors to explore virtual environments and interact with digital objects in real time. In communication, computer vision can be used to create engaging visual content that conveys information more compellingly and memorably, for example, by creating AR or VR experiences that allow viewers to interact with digital content in real-world environments, or visualizations that make complex data and information more accessible and understandable.

2.1.4. Robotics

Robotics refers to the design, construction, operation, and use of robots (Aoun, 2017; Siau & Wang, 2018). It often refers to applying AI techniques in developing and operating robots. AI can play a key role in robotics by enabling robots to perceive and understand their environments, make decisions, and take actions based on their understanding. AI techniques, such as machine learning, computer vision, and natural language processing, can be used to enhance the capabilities of robots and enable them to perform more complex tasks.

Robotics play a significant role in museum exhibitions and communication by enhancing visitor experiences and providing interactive and engaging displays (Shiomi, Kanda, Ishiguro, & Hagita, 2006; Trahanias et al., 2005; Yamazaki, Yamazaki, Burdelski, Kuno, & Fukushima, 2010). Their typical applications in museums include interactive exhibits, educational demonstrations, AR, guided tours, and art installations (Fig. 7). Robotics can be used to create interactive exhibits where visitors can engage with robots and learn about their functions and capabilities. For example, a robot arm exhibit can show visitors how robots can be used in the manufacturing and assembly lines. Robotics can be used to demonstrate scientific principles and technological advancements in educational settings. Visitors can learn about the latest developments in robotics and their use in fields such as medicine and space exploration. Robotics can be integrated with AR technology to create an immersive visitor experience. AR can be used to project virtual images onto real-world objects, such as robots, to provide additional information and enhance learning experiences. In guided tours, robots can guide visitors through museum exhibits,

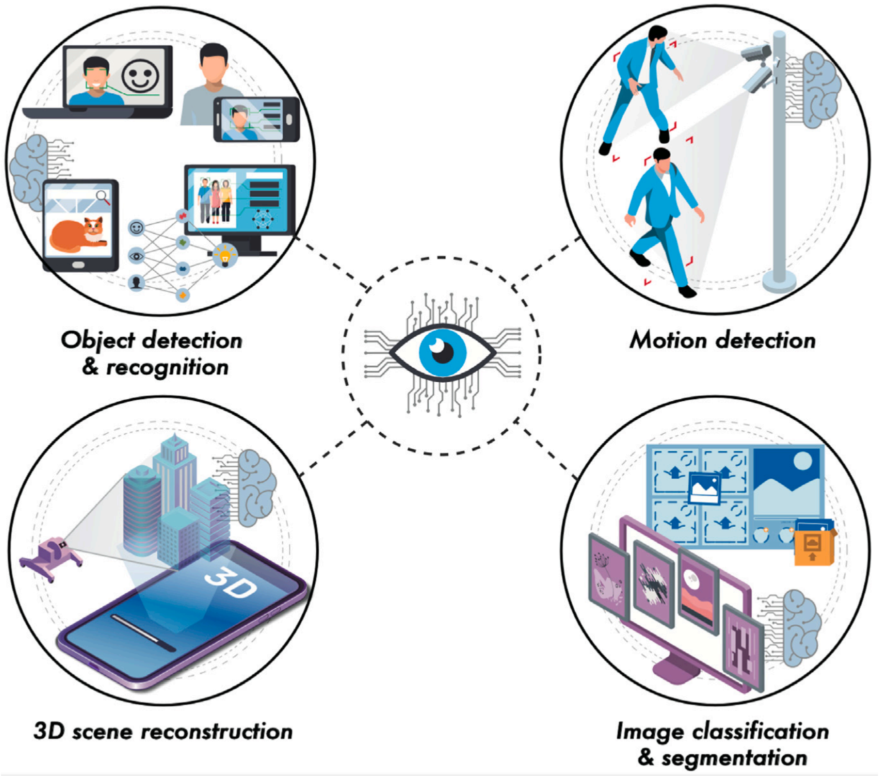

Fig. 6. Computer vision in museum exhibitions.

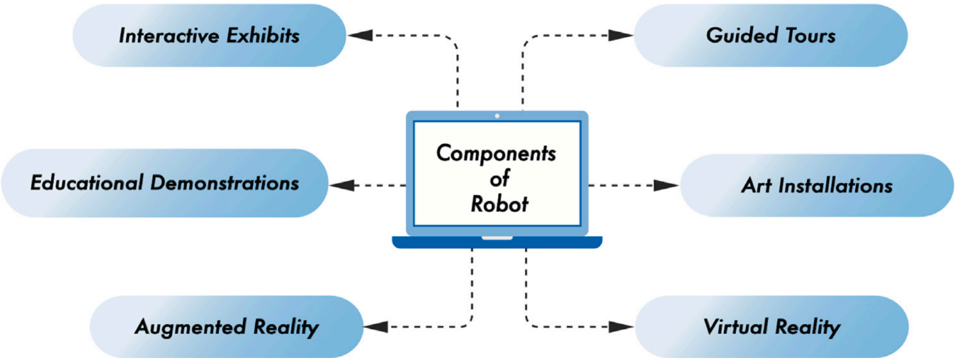

Fig. 7. Robotics in museum exhibitions.

provide information about the exhibits, and answer questions. These tours can be customized based on visitors' interests, making the experience more personalized. Robotics can also be used to create unique art installations that combine technology and art, and robots can be programmed to create paintings, sculptures, or installations, providing visitors with unique creative experiences.

2.1.5. *Recommendation systems*

Recommendation systems are a type of AI that learns and reciprocates human decision-making abilities to provide feedback to users for products, services, or content in which they might be interested (Isinkaye, Folajimi, & Ojokoh, 2015; Shani & Gunawardana, 2011). They use data analysis and ML algorithms to analyze patterns in user behavior and preferences to make personalized recommendations.

Recommendation systems in museum exhibitions and communications, such as personalized exhibit recommendations, interactive wayfinding, digital guides, social media integration, and AR experiences, can help enhance visitor experience and engagement (Fig. 8). Personalized exhibit recommendations can be used to suggest exhibits based on visitors' interests and past behaviors. For example, a visitor interested in ancient history might be recommended an exhibit of Egyptian artifacts. Interactive wayfinding can be made more engaging and interactive using recommendation systems. Visitors can be recommended routes to follow based on their interests and preferences. Digital guides can be used to create personalized for visitors. This includes recommended exhibits, activities, and restaurant recommendations. Social media integration can be used to suggest posts to visitors. For example, visitors may recommend a photo spot or unique exhibit to post on Instagram. AR experiences can also be customized based on visitor interests. For example, visitors interested in astronomy may be recommended an AR experience that allows them to explore the solar system.

2.2. *Immersion technologies*

Immersive technologies are computer-generated environments that simulate physical presence and sensory experiences, allowing users to feel fully immersed in a digital environment (Suh & Prophet, 2018;

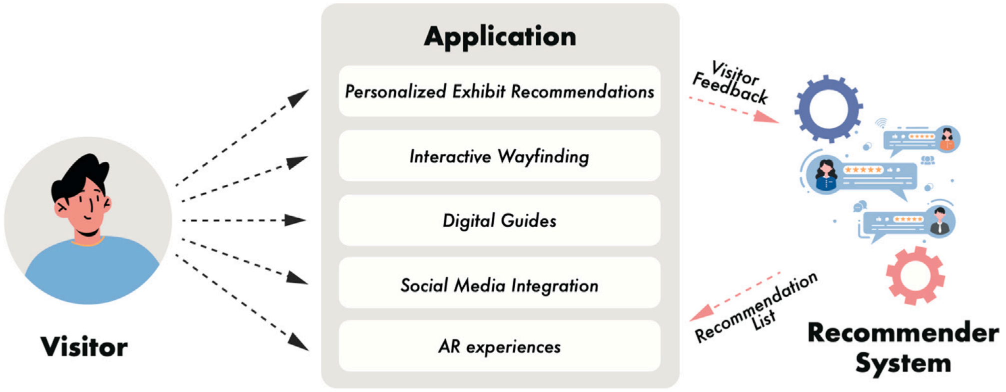

Fig. 8. Recommendation systems in museum exhibitions.

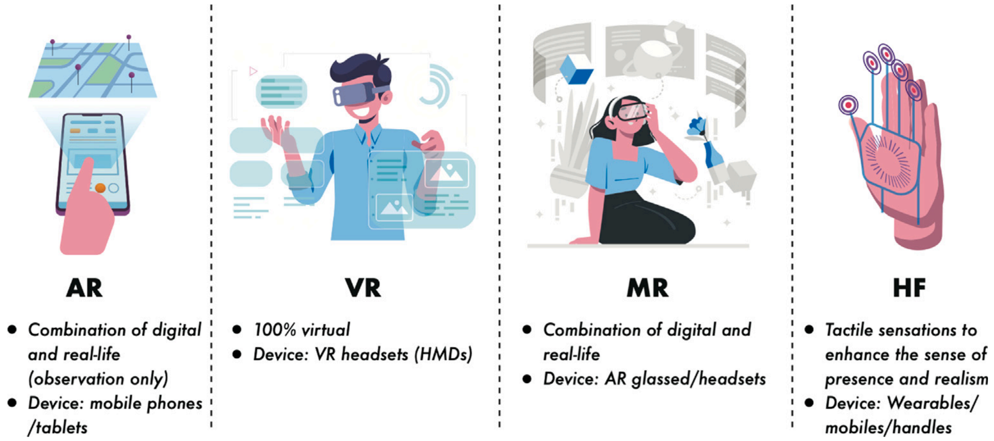

Fig. 9. Classification of immersion technologies.

Tang, Chau, Kwok, Zhu, & Ma, 2022). These technologies can create realistic 3D environments where users can interact using various devices such as head-mounted displays, handheld devices, or projected screens. Typical immersive technologies include VR, AR, MR, and haptic feedback (HF) (Fig. 9). Popular applications of immersive technologies in museum exhibitions include virtual tours, historical reenactments, multisensory experiences, educational content, accessibility, informational overlays, 3D models and animations, and interactive exhibits (Fig. 10).

2.2.1. *Virtual reality*

A computer-generated simulation of a three-dimensional (3D) environment that can be experienced using a head-mounted display (Sherman & Craig, 2018), VR allows users to interact with the environment and move around in the virtual space. The VR experience combines computer graphics, audio, and other sensory stimuli to simulate realistic environments. A headset or display device covers the user's eyes and ears and typically features a high-resolution screen that displays the 3D environment. The device may also include built-in speakers or headphones that provide immersive audio. The user's movements and actions are tracked by sensors or cameras placed around the room, allowing the virtual environment to respond to their movements in real-time. For example, if a user moves their head, the display device adjusts the view in the virtual environment to match the new perspective.

In museum exhibitions and communication, VR technology has become an increasingly popular tool, providing visitors with an immersive and interactive experience that can enhance their understanding of and engagement with the content (Fig. 10) (Bruno et al., 2010; Wojciechowski, Walczak, White, & Cellary, 2004). Typical applications include virtual tours, historical re-enactments, multi-sensory experiences, educational content, and accessibility. VR can be used to create virtual museum tours, allowing people to explore museum exhibits and collections from anywhere in the world. Visitors can move through museums, view artifacts closely, and interact with digital content in a way that is not possible through traditional exhibitions. VR can be used to recreate historical events or periods, allowing visitors to experience life in the past. For example, a VR experience can recreate a historical battle or a day in the life of a famous historical figure. It can also be used to create multi-sensory experiences, allowing visitors to see, hear, touch, and smell exhibits to create a more immersive and engaging experience for visitors. In addition, VR can be used to provide educational content in a fun and interactive manner, allowing visitors to explore the human body or travel through space to learn about planets. Finally, it can make exhibitions more accessible to people with disabilities or mobility issues, providing an alternative to physical exhibitions that are difficult to navigate or inaccessible.

Although VR technology has existed for decades, recent advancements in hardware and software have made it more accessible and affordable. Some of the most popular VR headsets on the market are the Oculus Quest 2, HTC Vive, and PlayStation VR. Additionally, many video games and other applications offer VR modes and experiences.

2.2.2. *Augmented reality*

AR is an interactive experience in a real-world environment in which objects are enhanced using computer-generated information (Billinghurst et al., 2015; Carmigniani & Furht, 2011). It is typically experienced through a mobile device or headset that overlays digital information on top of a user's real-world view. It combines computer-generated images, sounds, and other sensory stimuli with a user's physical environment to create an enhanced interactive experience. AR technology can be used with various devices, including smartphones,

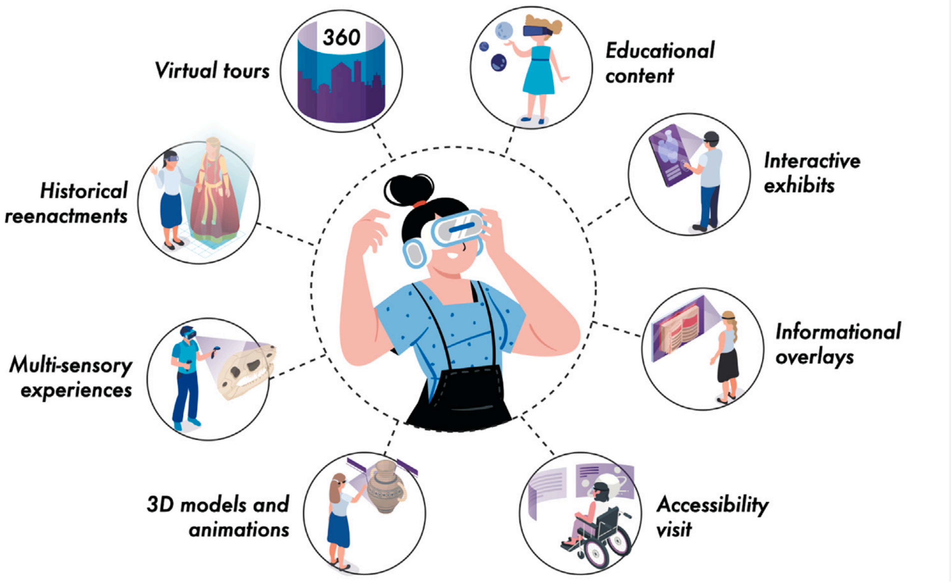

Fig. 10. Immersion technologies in museum exhibitions.

tablets, smart glasses, and other wearable devices. These devices use cameras and sensors to detect and track the user's physical environment and then overlay digital information onto it. AR can also provide visitors with enhanced and interactive experiences, such as informational overlays, 3D models and animations, historical reenactments, interactive exhibits, and accessibility (Keil et al., 2013). It can be used to provide informational overlays on exhibits, thereby providing visitors with additional context and information. For instance, a user can point to their smartphone or tablet at an exhibit, and AR technology can overlay information, such as the exhibit's history, background, or significance, on the screen. AR can be used to create three-dimensional (3D) models and animations of exhibits, allowing visitors to explore them in greater detail. A typical application of AR technology is to create a 3D model of a dinosaur skeleton, allowing visitors to view the exhibit from different angles and interact with it in a more engaging manner. AR can also be used to recreate historical events or periods that allow visitors to experience life in the past, create interactive exhibits allowing visitors to interact with digital content that is not possible through traditional exhibitions, and make exhibitions more accessible to people with disabilities by providing, for instance, an AR experience through audio descriptions or visual aids for exhibits.

AR technology has the potential to enhance museum exhibitions and communication by providing visitors with a more engaging and interactive experience. Using AR, museums can attract new audiences, provide educational content in a fun and interactive manner, and make their exhibits more accessible to a wide range of people.

2.2.3. Mixed reality

MR combines VR and AR, allowing users to interact with digital and physical objects (Milgram & Kishino, 1994; Piumsomboon et al., 2017). It is typically experienced through head-mounted displays and can be used in various fields, such as education, healthcare, and entertainment. Unlike VR, which completely immerses the user in a simulated environment, or AR, which overlays digital information in the real world, MR combines the two by allowing virtual objects to interact with the real world more naturally.

A key difference between MR and other immersive technologies is that MR objects can interact with real-world objects and the environment in a more natural manner. For example, a virtual ball in an MR experience could bounce off a real-world table, or a virtual car could be driven on a real-world road. This interaction is made possible through advanced tracking and mapping technologies that allow the MR device to understand and respond to the real world in real-time.

Another advantage of MR technology is that it allows users to collaborate and share their experiences more naturally and intuitively. For example, multiple users wearing MR headsets can interact with the same virtual objects in a shared physical space, thus providing a new level of collaboration and interaction.

2.2.4. Haptic feedback

HF involves using technology to provide users with tactile sensations such as vibration or pressure (Lécuyer, 2009; Pitts et al., 2012), and can be used in VR, AR, and other immersive experiences to enhance the user's sense of presence and realism. It uses motors or actuators to create vibrations or other physical sensations in response to user input or specific events in the device or software. For instance, when typing on a smartphone keyboard, HF can simulate the feeling of pressing physical keys, making it easier for users to type accurately without looking at the screen. Typical HF includes (i) tactile feedback, which provides a sensation of touch or pressure on the skin; (ii) kinesthetic feedback, which provides a sensation of movement or force in the muscles and joints; (iii) thermal feedback, which provides a sensation of temperature change on the skin; (iv) vibration feedback, which provides a sensation of oscillation or vibration on the skin; and (v) force feedback, which provides a sensation of resistance or pressure on the skin.

HF can be used in VR/AR/MR systems to create a more immersive experience. By providing physical feedback in response to actions in the virtual world, HF can make an experience more realistic and engaging. HF technology has the potential to enhance museum exhibitions and communication experiences by providing visitors with an engaging, interactive, immersive, and more accessible experience.

2.3. Additive manufacturing

Museum exhibitions include digitizing and prototyping historical artifacts and art collections. Additive manufacturing, also known as three-dimensional (3D) printing, is a powerful tool for rapidly prototyping historical artifacts and artworks. 3D object data for AM can be reconstructed using 3D scanning or computer-aided design (CAD) modeling. In particular, historical artifacts can be digitized with 3D scanning and then replicated by AM, providing a solution for preventing and spreading cultural heritage.

2.3.1. 3D scanning for object digitization

3D scanning is a crucial technique widely employed for digitizing cultural heritage, which is particularly important for galleries, libraries, archives, and museums (GLAM) sector. It utilizes principles such as laser or structured light to digitally capture the three-dimensional geometry of artifacts, resulting in high-precision 3D model data. These digitized 3D virtual assets not only aid in the long-term preservation of cultural heritage but also enable a multitude of applications, including virtual exhibitions, educational purposes, and the creation of 3D-printed replicas.

3D scanning systems typically consist of a scanning device, calibration tools, and software for data processing and model reconstruction. Various 3D scanning technologies exist, such as laser triangulation, structured light, and photogrammetry, each with its own advantages and limitations in terms of accuracy, resolution, and suitability for different types of objects and materials.

The digitization of cultural heritage through 3D scanning has become increasingly prevalent in recent years, driven by the need for preservation, accessibility, and novel means of engagement. For instance, initiatives like the CyArk Project (Underhill, 2018) and the Smithsonian 3D Digitization Program (Horton & Xiong, 2016) have extensively created digital repositories of cultural heritage sites and artifacts using state-of-the-art 3D scanning techniques. These virtual assets, once created, can be integrated into various DTTs discussed in this paper, such as virtual reality, augmented reality, and 3D printing, to enhance visitor experiences and provide new avenues for education, research, and cultural appreciation.

Recent studies have highlighted the significance of 3D scanning in digitizing and creating virtual assets of cultural heritage objects. Atik et al. demonstrated the effectiveness of high-resolution 3D scanning in capturing intricate details of historical artifacts, enabling the creation of accurate digital replicas for conservation and research purposes (Atik, Duran, Yanalak, Seker, & Ak, 2023). Similarly, Ziegler et al. explored the integration of 3D scanning and printing technologies for producing high-fidelity replicas of fragile or restricted museum objects, enhancing their accessibility for tactile exhibitions and educational programs (Ziegler et al., 2020).

2.3.2. 3D printing for object fabrication

AM (3D printing) is the process of creating 3D objects by adding successive layers of material, usually starting from a digital 3D model (Gibson et al., 2021; Lee, An, & Chua, 2017; Shahrubudin, Lee, & Ramlan, 2019; Wong & Hernandez, 2012). The materials used for AM vary widely, from plastics to metals, ceramics, and even food. AM has many applications across many fields, including manufacturing, architecture, engineering, medicine, and the arts. It allows for the creation of complex shapes and structures that are difficult or impossible to fabricate using traditional manufacturing methods. AM is relatively fast and affordable, making it accessible to a wide range of users.

The AM process consists of model creation, printing, and post-processing. During model creation, a 3D model (the mathematical representation of a 3D surface) is generated using CAD software or 3D scan data (Gibson et al., 2021; Zheng, Guo, et al., 2018). The 3D model is then exported as an STL or OBJ file before being sent to the AM software. AM software can slice a 3D model into horizontal cross-sectional layers with specific print settings, such as layer thickness and additional support. The sliced file is then sent to a 3D printer via a wireless or cable connection. 3D printers use different techniques to create solid objects, such as laser-curing liquid resins or fusing polymer powders with heat. Many printers can run unsupervised and automatically refill materials from cartridges. Printed parts may require various post-processing steps, such as rinsing with isopropyl alcohol, manual support removal, or cleaning with compressed air. Some of these processes have been automated. Parts can be used directly or post-processed by machining, painting, or joining. AM often complements conventional manufacturing methods, such as creating molds for custom parts.

The creation of ISO/ASTM 52900 in 2015 aimed to standardize the classification of 3D printers and AM technologies with seven established process categories: vat polymerization, material extrusion, powder bed fusion, material jetting, binder jetting, direct energy deposition, and sheet lamination (Fig. 11) (Standard, 2012). These AM technologies cover various 3D printable materials, ranging from polymers and ceramics to alloys and functional materials. Vat polymerization, such as stereolithography (SLA), is a 3D printing technology that uses a liquid resin that hardens when exposed to light to create objects layer by layer (Melchels, Feijen, & Grijpma, 2010; Patel et al., 2017; Zheng, Fu, Du, Wang, & Yi, 2018; Zheng, Guo, & Watanabe, 2021; Zheng et al., 2022; Zheng, Watanabe, Wang, Chen, & Naito, 2024). Material extrusion, also known as fused filament fabrication (FFF) or fused deposition modeling (FDM), involves layer-by-layer deposition of a thermoplastic material to create a 3D object (Carneiro, Silva, & Gomes, 2015; Mohamed, Masood, & Bhowmik, 2015). Powder bed fusion, such as selective laser sintering (SLS) and selective laser melting (SLM), uses a bed of powder materials, such as plastic or metal, to create 3D objects layer by layer (Guo, Zheng, Yang, Yang, & Yi, 2019; Singh, Mahender, & Reddy, 2021; Sun, Brandt, & Easton, 2017; Zhou et al., 2021). Material jetting employs inkjet printing to create complex 3D objects. It works by jetting tiny droplets of a liquid photopolymer onto a build platform, which is then solidified using UV light (Gibson et al., 2021b; Gülcan, Günaydın, & Tamer, 2021). A key advantage of material jetting is that it enables the printing of multi-material and multicolor objects as end-use products (Skylar-Scott, Mueller, Visser, & Lewis, 2019). Binder jetting uses a printer to selectively deposit a liquid binder onto a layer of powdered material, such as a metal or ceramic powder, to create a solid object (Gibson et al., 2021a; Ziaee & Crane, 2019). Direct energy deposition (DED) uses a focused energy source, such as a laser or electron beam, to melt and fuse materials to create 3D objects (Lewandowski & Seifi, 2016). This process is called laser metal deposition (LMD) or laser-engineered net shaping (LENS) (Gu et al., 2021). Sheet lamination is a 3D printing process in which thin sheets of material are layered on top of each other to create 3D objects (Friel & Harris, 2013; Hehr & Norfolk, 2019).

Among AM technologies, FDM is the most popular because it is low-cost, easy to use, and enables the creation of plastic models of different colors. SLA is another popular material owing to its outstanding surface finish and wide variety of resin materials.

2.4. Internet of things

The IoT is a network of interconnected physical devices, vehicles, buildings, and other objects embedded with sensors, software, and network connectivity, allowing them to collect data and exchange these with other systems (Da Xu, He, & Li, 2014; Holler et al., 2014; Li, Xu, & Zhao, 2015). IoT connects devices to the Internet, enabling remote access and control and allowing them to operate autonomously. It can be utilized in museum exhibitions to enhance visitor experiences and provide innovative ways of engaging with displayed artifacts, such as interactive displays, smart lighting and climate control, virtual guides, crowd monitoring and management, collection management, and enhanced AR experiences (Fig. 12).

IoT systems typically comprise three main components: sensors, devices, networks, and software. IoT devices are embedded in sensors, processors, and communication modules, allowing them to collect and transmit data from their environment to other devices or systems. Sensors can detect different data types, such as temperature, humidity, light, sound, motion, or location. These devices are connected to the Internet or private networks, allowing them to communicate with each other and other systems. The network may use different communication protocols, such as Wi-Fi, Bluetooth, Zigbee, or cellular. IoT systems use software applications to analyze the data collected by sensors and devices and control their behavior. The software can run on the devices, a cloud server, or an edge computing platform. Machine learning

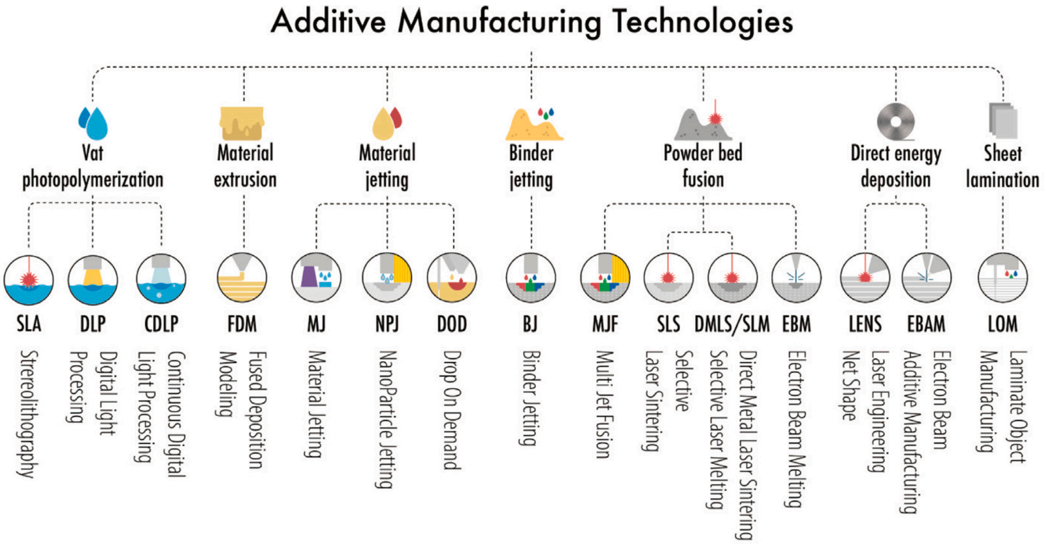

Fig. 11. Taxonomy of additive manufacturing technologies.

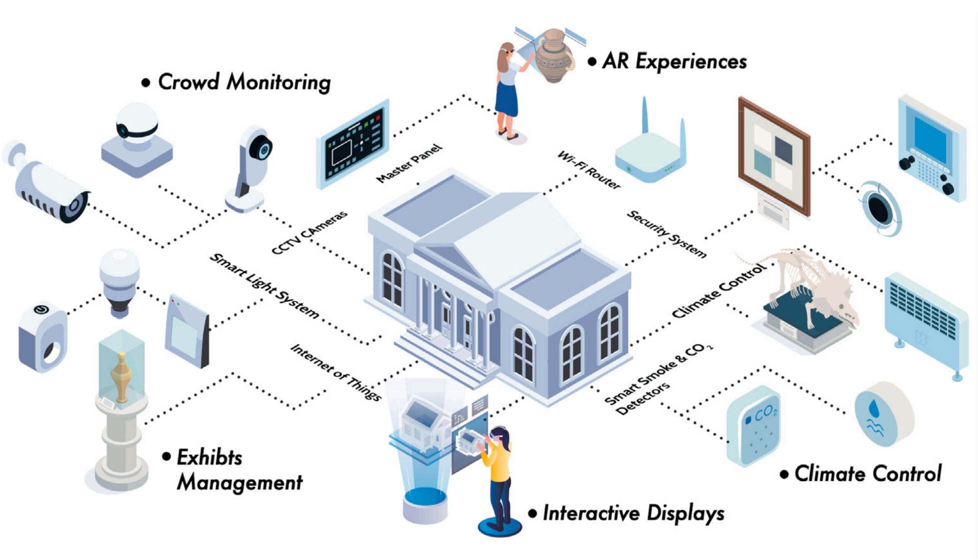

Fig. 12. Internet of Things in museum exhibitions.

algorithms or other techniques may be used to extract insights from the data and make predictions or decisions.

The benefits of the IoT include improved efficiency and productivity, improved customer experience, better decision-making, and safety. First, IoT devices can collect and analyze data from sensors and other devices, allowing businesses and organizations to optimize their operations, reduce costs, and increase productivity. For example, museums can use IoT sensors to monitor showcase performance and predict maintenance requirements, thereby reducing downtime and increasing efficiency. Additionally, IoT devices can be used to create personalized experiences for visitors, such as customized recommendations, targeted marketing, and improved support. For instance, a smart museum system may use IoT devices to automatically adjust temperature, lighting, and other settings based on the preferences of designers or visitors. Moreover, IoT data can provide insights into trends to help businesses make better decisions. For instance, a museum may use IoT sensors to track foot traffic in a store and optimize its artwork placement. Finally, IoT devices can be used to monitor and detect potential safety hazards and security threats.

2.5. Cloud computing

Cloud computing refers to providing computing services like storage, databases, servers, analytics, software, networking, and intelligence over the internet (also called “the cloud”) (Armbrust et al., 2010; Dillon, Wu, & Chang, 2010; Voorsluys, Broberg, & Buyya, 2011). It aims to provide faster innovation, greater resource flexibility, and cost efficiency through economies of scale and can play a significant role in enhancing museum exhibitions by providing several benefits and capabilities, such as scalable storage, virtual exhibitions, collaboration and sharing, content delivery, data analytics, disaster recovery, and backup, and cost efficiency (Fig. 13).

Cloud computing offers several benefits, including cost savings, speed, scalability, flexibility, reliability, and security. Cloud computing eliminates the need for businesses to invest in and maintain their IT infrastructure, thereby reducing capital and operational expenses. It also allows businesses to scale their computing resources up or down rapidly based on demand without purchasing or installing additional hardware. Furthermore, it provides customers with access to a range of computing resources, services, and applications, allowing them to

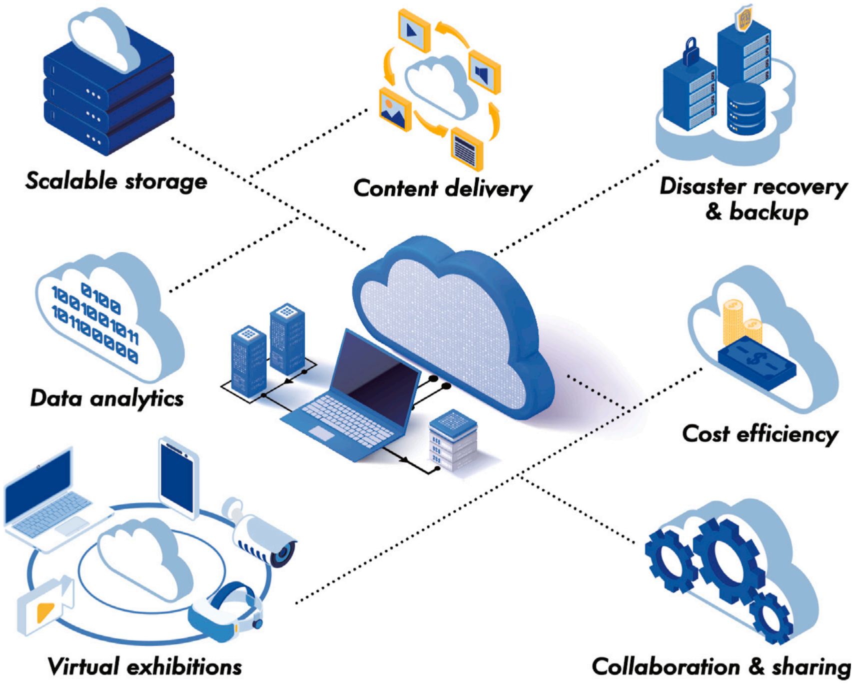

Fig. 13. Cloud computing in museum exhibitions.

tailor their computing requirements to their needs. Cloud providers offer high availability and redundancy, ensuring that data and applications are always accessible. For example, a context-aware museum guide system powered by cloud computing can quickly present information on exhibits to match visitor needs (Vahdat-Nejad, Navabi, & Khosravi-Mahmouei, 2018).

3. Digital transformation technologies in museum exhibitions

This section examines how DTTs are transforming various aspects of museum exhibitions, including exhibition design and curation (Section 3.1), accessibility and inclusion (Section 3.2), educational potential and long-term impact (Section 3.3), visitor experience data collection and analysis (Section 3.4), and collection and exhibit management (Section 3.5).

3.1. Designing and curating attractive exhibitions

DTTs are profoundly reshaping the way museum exhibitions are designed and curated. By integrating technologies such as VR, AR, AI, and 3D printing into exhibitions, curators and designers can create more immersive and interactive experiences that allow visitors to explore historical events and cultures in unprecedented ways. For instance, VR and AR can provide lifelike scenarios, AI-driven recommendation systems can offer personalized guidance to visitors based on their interests, and 3D printing can reproduce delicate or rare artifacts for visitors to closely observe and interact with. Effective collaboration among curators, technology experts, and designers is crucial to creating captivating exhibitions that resonate with modern audiences. Only by integrating multiple perspectives and expertise can museums fully harness the potential of digital technologies to tell innovative and compelling stories that engage a broader audience.

Table 1 provides a comprehensive overview of DTT applications in designing and curating appealing museum exhibitions. For example, AI-powered chatbots with embodiment and reflection features have been found to enhance visitors' learning and interaction with museum exhibits. AR can be combined with deep learning to facilitate more personalized learning experiences by offering visitors rich multimedia information and enhanced interactions with artifacts (He, Wu, & Li, 2018). Immersion technologies play a crucial role in enhancing visitor engagement in various museum settings and allow more profound exploration and understanding of exhibits through the recreation of historical environments and object manipulation (Hammady, Ma, Strathern, & Mohamad, 2020; Petrelli, 2019). Some studies emphasize the importance of 3D reconstruction integration at heritage sites, whereas others focus on the performance of different immersive devices, such as VR-based Oculus Quest and AR-based Magic Leap (Verhulst, Woods, Whittaker, Bennett, & Dalton, 2021). HF has emerged as a vital element for complementing visual immersion, as seen in TouchVR technology, which enables multimodal tactile sensations on the fingertips (Trinitatova & Tsetserukou, 2019). Table 1 highlights the application of AM, demonstrating its potential to create realistic replicas that improve visitor engagement and offer multisensory experiences (Di Franco, Camporesi, Galeazzi, & Kallmann, 2015).

DTTs have led to a significant paradigm shift in the design and creation of museum exhibitions. They enable the creation of interactive and engaging exhibit displays, personalized visitor experiences, and innovative storytelling and narration techniques (Fig. 14). In addition, they facilitate productive collaboration among curators, technologists, and designers to develop memorable experiences for museum visitors. The integration of DTTs in exhibit displays allows for interactive and multi-sensory experiences, enhancing visitors' understanding of and connections with the exhibits. Through the use of touchscreens, gesture-based interfaces, HF, and AR, visitors can access additional information, manipulate digital visualizations, and engage with immersive sensory elements associated with the presented artifacts. Roberts et al. redesigned three exhibitions using interactive touchscreen displays to help visitors appreciate real objects and artifacts they could not touch or manipulate and stimulate their curiosity, interest, and engagement (Fig. 14a) (Roberts et al., 2018).

Moreover, DTTs enable personalized visitor experiences through recommendation systems, digital guides, and mobile applications that track individual preferences, needs, and learning styles. AR and social-sensor mining techniques are applied to recommendation systems for personalized museum itineraries based on social network data, semantic analysis, data mining, machine learning, and beacon sensors to improve the visitor experience (Fig. 14b) (Torres-Ruiz, Mata, Zagal,

Table 1
An overview of the application of DTTs in designing and curating appealing museum exhibitions.

DTT type	Application	Visitor experience theme	Research strategies	Participants	Key findings	Impact on visitor engagement	Ref.
AI	Robotics-Chatbots	Impact of Chatbot appearance and language style on history education and museum experience	Evaluating Chatbot impact on museum experience through mixed-methods approach	34 Visitors	Chatbot model with embodiment and reflection enhances museum experience	Enhanced visitors' learning and interaction through Chatbots with embodiment and reflection	Noh and Hong (2021)
Immersive, AI	AR, CNN	Enriching Museum Experience through Multimedia Information and Artifact Interaction	Deep Learning for artifact recognition, user-centered questionnaire-based survey, and evaluation models	30 Students	AR Application enhances connection with artifacts and provides richer multimedia information	Improved AI and personalized learning experiences	Khan et al. (2021)
Immersive	AR	Effect of information and augmented scenes on visitor evaluation and purchase intent	Experimental study on AR design's impact on visitor experience and intent to pay more	225 Visitors	Dynamic verbal cues surpass visual cues, especially with enhanced virtual presence, in increasing willingness to pay	Boost Engagement and Payment Intent via Dynamic Verbal Cues and High Virtual Presence in AR	He et al. (2018)
Immersive	AR, NI	Improving museum artifact accessibility and interaction	AR-NI integration utilizes off-the-shelf components for virtual interaction with museum object replicas	50 Visitors	The system revolutionized virtual interaction with museum artifacts	Enhanced visitor interaction with digital content improved accessibility and engagement with museum artifacts	Kyriakou and Hermon (2019)
Immersive	VR, AR	Heritage site tour through 3D reconstruction	Qualitative study: 3D reconstructions in heritage visits for museum integration guidelines	20 visitors, 11 visitors	AR is preferred for present-past comparison, VR for contextualizing exhibits in monumental settings	AR/VR boosts visitor engagement at heritage sites by museum effective 3D reconstruction integration guidelines	Petrelli (2019)
Immersive	VR, AR	Comparison of user experiences of immersive technologies (VR and AR) in an art gallery exhibition	Assessing user experience: Oculus Quest (VR) vs. Magic Leap and Mira Prism (AR) using a between-subjects design	368 Visitors	Oculus Quest (VR) outperformed Magic Leap and Mira Prism (AR) in immersive gallery experiences	Consider immersion in designing to enhance visitor engagement, as VR may offer greater immersion than AR	Verhulst et al. (2021)
Immersive	VR	The experience of art appreciation	Experimental comparison of Desktop VR, HMD VR, and physical exhibitions	78 Students	Improve the design of object size and the interaction in the VR context	Perception of the painting by the participants was similar regardless of the viewing method	Lin, Chen, and Lin (2020)
Immersive	TouchVR	Multimodal HF for Enhanced Immersion and Interaction	Development and Demonstration of TouchVR Technology	–	TouchVR's DeltaTouch enables multimodal tactile sensations on fingertips, including weight, slippage, encounter, softness, and texture	TouchVR enhances visitor engagement through tangible and realistic virtual environments, fostering deeper exploration and understanding	Trinitatova and Tsetserukou (2019)
Immersive	MR	Measuring the impact of MR on museum visit satisfaction	Empirical analysis using the visitor experience model for MR	726 visitors	MR transforms museum visits, enhancing visitor satisfaction with functional and experiential elements	MR in museums blends heritage and technology, enhancing visitor satisfaction and engagement	Trunfio, Campana, and Magnelli (2020)
Immersive	ODV	The automobile and road museum visit experience	Data from two ODV-based museum installations: HMD-based rally simulator and projector-based road grader simulator with HF	215 Visitors	Immersion, interactivity, and HF enhance museum installations	ODV installations enhance visitor interactivity and HF, making museums more desirable to visit	Hakulinen, Keskinen, Mäkelä, Saarinen, and Turunen (2018)
Immersive, 3D printing	3D immersive, 3D printing	Exploring artifacts through object manipulation	Comparative experiments: traditional displays, VR, and 3D prints	60 Visitors	Visitors prefer 3D immersion over traditional museum displays	Using these technologies in museums enriches visitor experience, fostering deeper connections with artifacts	Di Franco et al. (2015)

(*continued on next page*)

Table 1 (*continued*).

DTT type	Application	Visitor experience theme	Research strategies	Participants	Key findings	Impact on visitor engagement	Ref.
3D printing	3D Printing, XCT	Multisensory Experiences and Verisimilitude of 3D Printed Replicas	Mixed-methods approach with statistical and standard UX methods	140 Visitors	Realism, clarity (visual and tactual), and detail level are crucial for 3D printed replicas	3D printed replicas enhance visitor engagement, creating memorable museum experiences for diverse visitors	Wilson, Stott, et al. (2018)

Guzmán, Quintero, & Moreno-Ibarra, 2020). This customization ensures that museums cater to a broader audience and facilitate more meaningful connections with their collections. DTTs also enhance storytelling and narration techniques, thereby enabling the creation of captivated and comprehensible narratives. Interactive multimedia storytelling was applied to create a Transmedia Storytelling experience to help visitors understand the cultural and natural heritage of Maderia in Spain, demonstrating the potential of multimedia presentations in cultural heritage (Fig. 14c) (Dionisio & Nisi, 2021). By utilizing audio guides with natural language processing, VR experiences, and multimedia presentations, museums can effectively convey historical, cultural, and artistic contexts and stimulate visitor's engagement and curiosity. Finally, DTTs foster collaboration among curators, technologists, and designers, resulting in innovative and multidisciplinary exhibitions that blend traditional knowledge with cutting-edge technology. Darzentas et al. leveraged various technologies, including data capture, analysis, visualization, and inter-personalization, to enhance stakeholder, researcher, and audience engagement in co-designing museum visitors' experiences. Utilizing personal data-inspired informed design activities while addressing privacy, ownership, and transparency challenges during the COVID-19 pandemic (Fig. 14d) (Darzentas et al., 2022). Such a collaborative approach can create accessible, immersive, and inspiring exhibitions that resonate with modern audiences and advance museum educational missions.

In addition to the aforementioned technologies, museums are exploring emerging approaches such as games, virtual production, and social media platforms to attract and engage audiences. Gamified interactive experiences can increase visitor participation and immersion, particularly appealing to younger generations. Virtual production techniques enable museums to create vivid digital content for special exhibition promotions, behind-the-scenes tours, and more. Social media platforms allow museums to interact with audiences in real-time, disseminate event information, spark cultural topic discussions, and expand their influence. One notable example of successful DTT integration in exhibition design is the "Future World: Where Art Meets Science" exhibit at the ArtScience Museum in Singapore (Museum, 2021). This immersive installation combines interactive digital art with advanced technology, allowing visitors to co-create and manipulate digital content in real-time. The exhibit features a 15-meter-tall digital waterfall, a virtual ecosystem that evolves based on visitor interactions, and a room with over 170,000 LED lights responding to visitor movements. By seamlessly blending art, science, and technology, this exhibit creates a highly engaging and memorable experience for visitors of all ages. Scholars have investigated the potential of games, virtual production, and social media to engage museum audiences. Nofal et al. examined the impact of gamification on visitor engagement and learning outcomes in museum contexts, finding that gamified experiences can increase motivation, participation, and knowledge retention (Nofal et al., 2020).

Regarding virtual production, Checa and Bustillo explored virtual reality and cinematic techniques for creating immersive and emotionally engaging museum experiences (Checa & Bustillo, 2020). Focusing on social media, Budge and Burness analyzed how museums leverage platforms like Instagram and Twitter to build online communities, share collections, and foster dialogues with diverse audiences (Budge & Burness, 2018). Cross-sector collaborations between museums and the gaming, film, and internet industries are also rising, bringing more possibilities for developing innovative exhibition content and cultural creative products. However, in the process of incorporating these new approaches, museums need to balance the application of technology with the goals of content presentation, aesthetic experience, and knowledge dissemination.

In summary, DTTs have revolutionized museum design and curated exhibitions, enabling interactive and engaging displays, personalized visitor experiences, and innovative storytelling and narration techniques. Through the collaborative efforts of curators, technologists, and designers, museums can leverage DTTs to create immersive, multisensory, and accessible experiences that cater to diverse audiences and strengthen their educational missions. Their effective implementation enables museums to establish profound connections with visitors and remain relevant in today's rapidly evolving digital era.

3.2. *Enhancing accessibility and inclusion*

Integrating DTTs in museum exhibitions significantly enhances accessibility and inclusivity by addressing various barriers that may hinder diverse visitors from fully engaging with the content. By leveraging technologies such as assistive devices, multi-sensory displays, and multilingual interfaces, museums can create welcoming and equitable spaces that cater to a wide range of physical, sensory, cognitive, and sociocultural needs. For instance, audio descriptions and tactile exhibits can make the experience more accessible for visually impaired visitors, while closed captioning and sign language interpretation can benefit those with hearing impairments. Furthermore, DTTs can help bridge linguistic and cultural gaps by providing content in multiple languages and offering context-sensitive information that fosters understanding and appreciation among visitors from different backgrounds. By harnessing the potential of these technologies, museums can fulfill their crucial role in making culture, science, and the arts equally available to all citizens, ensuring that their exhibitions are genuinely inclusive and accessible.

Table 2 provides an overview of how DTTs are used to enhance accessibility and inclusion in museum exhibitions. For instance, immersive audio descriptions are used to enhance the cognitive, physical, and sensory access for blind and visually impaired visitors (Vaz, Fernandes, & Veiga, 2018a). Mobile AR has enriched museum experiences for deaf and hard-of-hearing visitors (Baker, Bakar, & Zulkifli, 2020). AM plays a significant role in fostering inclusivity by creating tactile maps and models (Rener, 2017), interactive 3D-printed models for architectural details (Rossetti, Furfari, Leporini, Pelagatti, & Quarta, 2018), and haptic replicas for the tactile exploration of cultural heritage content (Pistofidis et al., 2023). IoT enables indoor navigation systems for blind and visually impaired visitors, allowing them to enjoy self-guided accessible tours (Usuda-Sato, Nakayama, Fujiwara, & Usuda, 2019).

DTTs positively impact museum accessibility and inclusion. These technologies not only enhance the experiences of visitors with disabilities but also benefit from engaging and educating diverse audiences (Comes et al., 2020). Fig. 15 shows examples of enhanced accessibility and inclusivity using DTTs. First, DTTs enable improvements in physical accessibility by utilizing VR, AR, and MR to create digital representations of exhibitions, allowing individuals with mobility impairments or those unable to visit the museum in person to engage

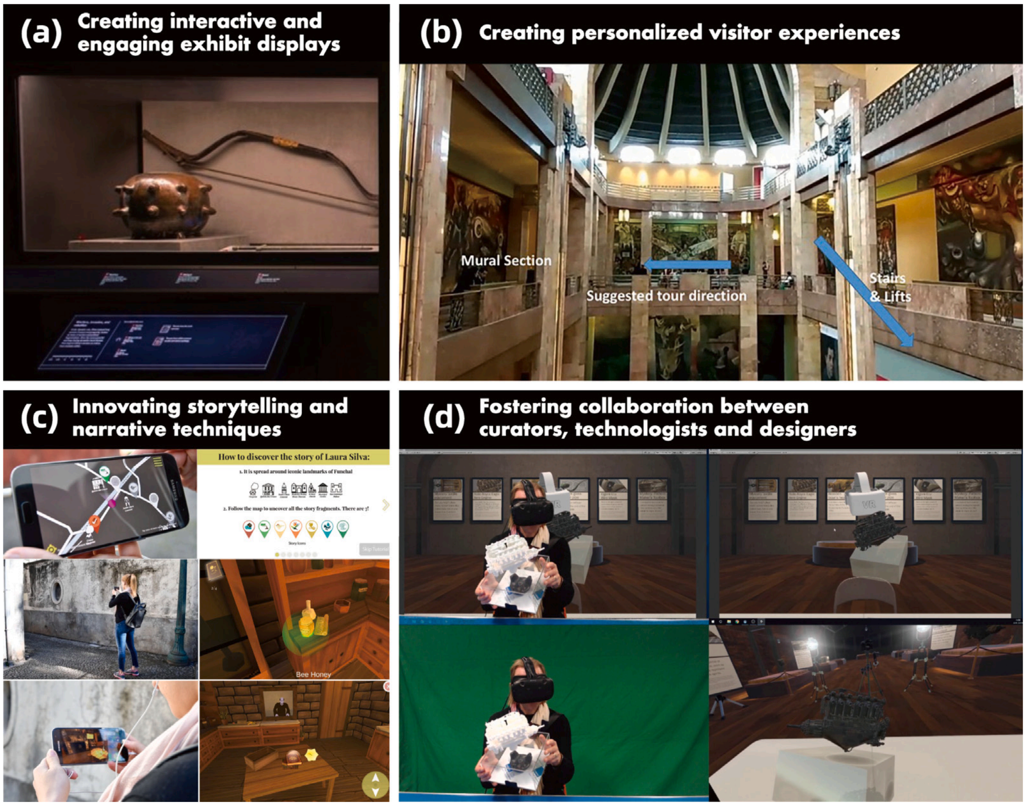

Fig. 14. Examples of exhibition features with DTT. (a) Interactive touchscreen display for real objects and artifacts appreciation (Roberts et al., 2018). Copyright 2018, ACM. (b) Personalized museum itineraries with AR and social-sensor mining techniques (Torres-Ruiz et al., 2020). Copyright 2020, Springer-Verlag London Ltd. (c) Transmedia storytelling for understanding Madeira's cultural and natural heritage (Dionisio & Nisi, 2021). Copyright 2021, the authors. (d) Collaborative co-designing of museum visitor experiences with data-driven technologies (Darzentas et al., 2022). Copyright 2022, the authors.

with the content (Fig. 15a) (Hammady et al., 2020; Scianna, Gaglio, Grima, & La Guardia, 2020; Sørensen & Hansen, 2017). IoT devices assist visitors in navigating museum spaces by providing real-time information on accessible routes and facilities through features such as indoor mapping (Puddu, Popescu, Murroni, & Fadda, 2021). Second, they enhance sensory accessibility by integrating audio descriptions, transcripts, sign language interpretations, and HF devices into exhibits (Fig. 15b) (Pistofidis et al., 2021; Vaz et al., 2018a; Vi, Ablart, Gatti, Velasco, & Obrist, 2017). These technologies are accessible through mobile applications, touchscreens, or interactive kiosks; cater to individuals with visual, auditory, or other sensory impairments, and offer alternative methods for accessing information and tactile experiences.

Third, cognitive accessibility is addressed through AI-driven personalization and adaptive learning systems, tailoring the museum experience to individual cognitive abilities and learning preferences (Fig. 15c) (Duguleană, Briciu, Duduman, & Machidon, 2020; Germak, Lupetti, Giuliano, & Ng, 2015; Kaplan, 2023). Interactive and gamified experiences assist individuals with cognitive impairments in processing and retaining information (Bugeja & Grech, 2020). Finally, DTTs contribute to sociocultural inclusion by promoting diverse perspectives and cross-cultural understanding (Fig. 15d) (Smith & Iversen, 2014; Smørdal, Stuedahl, & Sem, 2014). AI-powered NLP and translation tools provide multilingual content, thereby facilitating communication between visitors from different linguistic backgrounds (Gaia, Boiano, & Borda, 2019; Varitimiadis, Kotis, Pittou, & Konstantakis, 2021). Additionally, VR and AR experiences highlight the cultural heritage of underrepresented or marginalized communities, allowing them to share their stories and contribute to larger museum narratives (Fig. 15e) (Amakawa & Westin, 2018). The Louvre Museum in Paris has successfully leveraged virtual reality technology to enhance accessibility for visitors with mobility impairments (H.T.C. Vive Arts, 2019). In collaboration with HTC Vive Arts, the museum developed a VR experience called "Mona Lisa: Beyond the Glass", which allows visitors to explore the iconic painting in unprecedented detail, regardless of their physical abilities. The immersive experience provides a virtual tour of the painting's history, symbolism, and restoration process, using interactive elements and 3D animations. This innovative application of VR technology demonstrates how museums can harness DTTs to create inclusive and accessible experiences for diverse audiences.

Integrating DTTs in museum exhibitions offers a promising avenue for enhancing accessibility and inclusivity. By leveraging DTTs, museums can overcome physical, sensory, cognitive, and sociocultural barriers, ensuring that all visitors can participate actively and benefit from the museum experience. Through adaptive and accessible exhibit designs, language translations, assistive technologies, participatory exhibits, remote access, and inclusive workforce practices, DTTs enable museums to create environments that cater to diverse needs and foster a sense of belonging and cultural understanding. By embracing these technologies, museums can fulfill their educational mission and strengthen their relevance in an increasingly digital and interconnected world. As technology advances, museums must embrace digital transformation and explore innovative ways to make their collections and narratives accessible to a wide range of audiences. Thus, museums can formulate a more inclusive and equitable cultural landscape that celebrates diversity and promotes learning and appreciation.

3.3. *Enhancing education potential and long-term impact*

DTTs provide a wealth of opportunities to enhance the educational value and long-term impact of museum exhibitions. By integrating personalized learning systems, interactive environments, gamification elements, and collaborative experiences, museums can create engaging and memorable educational experiences that cater to diverse learning styles and preferences. For example, adaptive learning algorithms can

Table 2
An overview of the application of DTTs in enhancing accessibility and inclusion.

DTT type	Application	Visitor experience theme	Target visitors	Accessibility and inclusion initiative	Key findings	Ref.
Immersive	Audio descriptions	Enhanced cognitive, physical, and sensory access to exhibits	Blind and visually impaired visitors	Develop audio-driven interactive exhibit, eliminating artifact replicas	Visitors had positive interactions, enhancing conceptualization and expressing interest in future use	Vaz et al. (2018a)
Immersive	VR, 3D technologies	Enhanced museum experience and museum education	Museum visitors and educational users	Enhancing remote museum access and supplemental materials for in-depth learning	Virtual museum provides interactive computer tours and 3D virtual reality with HTC Vive, enhancing visitor experience and facilitating remote museum education	Kersten, Tschirschwitz, and Deggim (2017)
Immersive	Mobile AR	Enhancing museum experiences for hearing impaired visitors	Hearing impaired visitors	MARHIME enhances museum experiences for hearing-impaired visitors using mobile AR technology	MARHIME model enhances experiences of hearing impaired visitors with a validated museum-based prototype	Baker et al. (2020)
Immersive	AR, HF	Improving accessibility for blind and visually impaired visitors	Blind and visually impaired visitors	Interactive 2.5D artwork relief with audio, background music, and localized verbal descriptions	Multimodal guide improved access to visual artworks for blind and visually impaired visitors	Cavazos Quero, Iranzo Bartolomé, and Cho (2021)
Immersive	MR, VR	Collaborative, immersive, and interactive museum experience	Autistic individuals (8-20 years old) with cognitive disabilities	VR aids cognitive disabilities integration through collaborative activities, communication, and creativity	VR museum project fosters creativity, collaboration, and develops 3D skills	Gea, Alaman, Rodríguez, and Martinez (2016)
3D printing, immersive	3D scanning, VR	Enhanced interaction, creativity stimulation through technology for cultural heritage	Young visitors	Fusing traditional exhibition methods with digital tech for immersive, inclusive cultural experiences	Digital transformation enhances young audience engagement and education in museums	Comes et al. (2020)
3D printing	3D tactile system	Color recognition through texture perception	Visually impaired visitors	Creating a tactile-color texture system for art appreciation	Grating textures enhance art accessibility for the visually impaired, informing 3D printed haptic devices	Shin, Cho, and Lee (2020)
3D printing	Tactile model of telescope	Understanding cutting-edge telescope technology and functionality	Blind and visually impaired and sighted visitors	Project produced 3D printed tactile models for inclusive science classes	3D-printed tactile models promoted accessibility and inclusion in museums by enhancing telescope comprehension	Usuda-Sato et al. (2019)
3D printing	Tactile maps and models	Navigational accessibility for visually impaired visitors	Visually impaired visitors	Automated 3D printing of tactile maps/models based on geographic data and design process	New method cuts costs, time, and boosts accessibility for visually impaired visitors with tactile maps/models	Rener (2017)
3D printing	Interactive 3D-printed models	Improved accessibility to architectural details	All visitors, including people with vision impairments	Enhancing visitor independent exploration through tactile and audio support	Visually impaired users embraced affordable 3D prints and interactive audio, enjoying independent exploration	Rossetti et al. (2018)
IoT, 3D printing	Smart exhibit	Haptic interaction with museum artifacts	Visually impaired visitors	Low-cost haptic ban removal and creation of tactile-enabled artifacts and maps	Identifies requirements and practices for tactile access to cultural heritage for visually impaired users	Pistofidis et al. (2021)
IoT, 3D digitization, 3D printing	Haptic replicas, tactile maps, 3D-printed models	Tactile exploration and interaction with cultural heritage content	Visually impaired visitors	Smart prototypes for visually impaired users to explore cultural heritage via touch and narration	Prototypes empowered visually impaired users for inclusive access and interaction with cultural heritage	Pistofidis et al. (2023)
IoT	Indoor navigation system	Accessibility and self-guided tours for blind and visually impaired visitors	Blind and visually impaired visitors	Blind MuseumTourer enables independent exploration and interactive accessibility for the blind and visually impaired in museums	Integrated tactile indications, BLE beacons, and dead-reckoning enable reliable indoor navigation for the blind and visually impaired visitors	Meliones and Sampson (2018)

tailor content and activities to individual visitors' interests, knowledge levels, and pace, ensuring a more effective and enjoyable learning process. Interactive exhibits and simulations can encourage active participation and hands-on exploration, promoting deeper understanding and retention of information. Gamification techniques, such as challenges, rewards, and leaderboards, can motivate visitors to engage more intensely with the content and foster a sense of accomplishment. Moreover, DTTs can facilitate collaborative learning experiences,

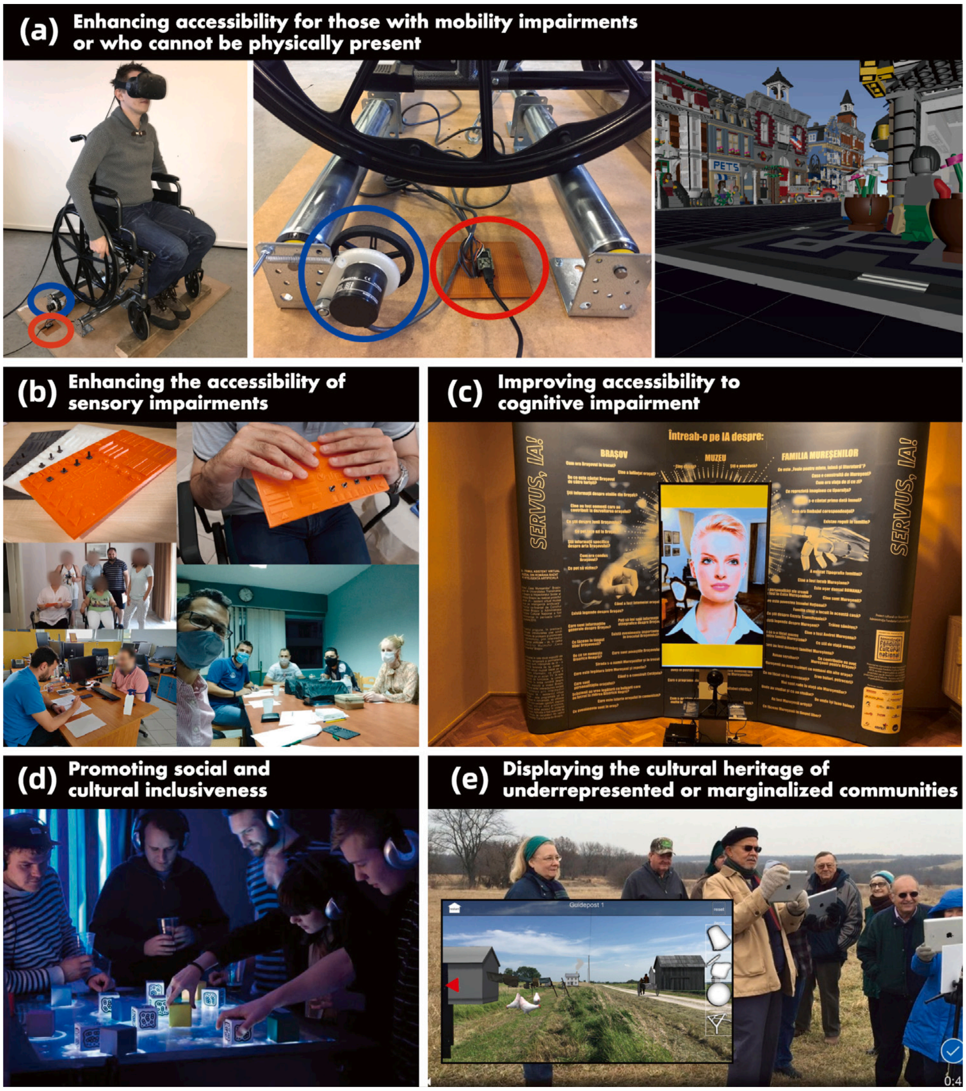

Fig. 15. Examples of accessibility and inclusion features with DTT. (a) A low-cost virtual reality wheelchair simulator (Sø rensen & Hansen, 2017). Copyright 2017, the authors. (b) Haptic performance assessment of 3D printing features of smart exhibits to support the visually impaired (Pistofidis et al., 2021). Copyright 2021, Elsevier Masson SAS. (c) Intelligent virtual agents that can interact with users in natural spoken language to improve the accessibility of information in history museums (Germak et al., 2015). Copyright 2020, the authors. (d) Stakeholders, researchers, and visitors can engage and discuss digital culture issues through interactive technology, increasing the inclusion of visitors in the exhibition (Smith & Iversen, 2014). Copyright 2015, Taylor & Francis. (e) A project at the New Philadelphia National Historic Landmark in Pike County, Illinois, addresses how buildings that have not survived can tell the story of history through AR (Amakawa & Westin, 2018). Copyright 2018, the authors.

such as multi-user virtual environments and social media integration, encouraging visitors to share knowledge, ideas, and perspectives. By leveraging these technologies, museums can create immersive and impactful educational experiences that inform, inspire, and empower visitors to continue learning beyond the museum walls.

Table 3 provides an overview of DTTs in enhancing educational potential and long-term impacts in museum environments, ranging from creating captivating storytelling experiences, developing additional educational resources, and encouraging active engagement among visitors. These studies employed diverse research strategies, including comparison experiments, Turing tests, pretest-posttest evaluations, simulation experiments, workshops, and user feedback evaluations. The participants ranged from museum visitors and middle-grade students to researchers. By employing these strategies and involving various participants, researchers can assess the effectiveness and benefits of DTTs in museum educational contexts. Many studies have found that DTTs positively impact visitor motivation, satisfaction, and learning outcomes in terms of educational potential. For instance, AI image synthesis has improved visitor motivation and satisfaction with online art education (Lee, Yun, Lee, Song, & Song, 2022). Immersive technologies such as AR, VR, and digital augmentations have been effective in improving science education in informal learning environments (Yoon, Elinich, Wang, Steinmeier, & Tucker, 2012), enhancing knowledge acquisition and motivation among schoolchildren visiting museums (Moorhouse, tom Dieck, & Jung, 2019), and fostering deeper exploration of artwork in art galleries (Leue, Jung, & tom Dieck, 2015). AM and scanning applications have been shown to engage young audiences in the cultural history of shoemaking (Turner et al., 2017) and provide visitors with enhanced learning, enjoyment, and interactivity through touchable 3D replicas of fossils (Wilson et al., 2017).

Numerous opportunities exist to enhance the educational potential of museum exhibitions through DTTs. Using AI algorithms, museums can personalize educational experiences for visitors based on their preferences, learning styles, and abilities (Fig. 16a) (Cepeda-Pacheco & Domingo, 2022; Pataranutaporn et al., 2021; Yang, 2022). These technologies transform static displays into dynamic and responsive installations, engaging visitors in a way that fosters deeper exploration of the subject matter (Fig. 16b) (Kennedy et al., 2021; Lee et al., 2021). Another powerful strategy enabled by DTTs is gamification, which introduces game-like elements or structures into exhibitions to

Table 3
An overview of the application of DTTs in enhancing education potential and long-term impact.

DTT type	Application	Visitor experience theme	Participants	Research strategies	Enhancing educational potential	Ref.
AI	AI image synthesis technology	Online art education	83 museum visitors	Comparison experiments	Synthesized images using self-uploaded photos improve visitor motivation and satisfaction	Lee et al. (2022)
AI, immersive	Virtualization and simulation, natural language processing, interaction technology	Talk and interact with Alan Turing's avatar	38 museum visitors	A simplified version of Turing's test	Stimulating children's interest in computer science and artificial intelligence and has a positive impact on education	Gonzalez et al. (2017)
Immersive	Digital augmentations	Science museum	119 middle grade students	Comparison experiments	Digital augmentations enhance science education by scaffolding knowledge construction in informal learning	Yoon et al. (2012)
Immersive	AR	Science museum	374 youth students	Comparison experiments	Multiple scaffolds boost learning potential in museums	Yoon, Anderson, Park, Elinich, and Lin (2018)
Immersive	AR	8 mathematical topics with a total of 275 exhibits	101 visitors	A pretest-posttest crossover field experiment	Museum visitors learn more from augmented exhibits than from non-augmented exhibits	Sommerauer and Müller (2014)
Immersive	AR	A museum in the UK	19 schoolchildren	Comparison experiments	AR can further enhance school children's knowledge acquisition and increase motivation to continue learning in museums	Moorhouse et al. (2019)
Immersive	Wearable AR	Art gallery settings	22 visitors	Comparison experiments	Helping visitors see the connections between paintings and personalize their learning experience	Tom Dieck, Jung, and tom Dieck (2018)
Immersive	Wearable AR	Art gallery	22 students	Simulation experiments	Helping users see new connections in the artwork and look deeper	Leue et al. (2015)
Immersive	AR, VR	science, art and history museums	–	Related research investigation, meta-analysis	AR/VR in museums enhance learning with material overlay, visualization, and simulation, mobile devices positively impact achievement and perceptions	Zhou, Chen, and Wang (2022)
Immersive	Interactive technologies	Science museums, history museums	–	Literature review	Interactivity types are vital for children's learning in museums, with promising strategies overlapping	Andre, Durksen, and Volman (2017)
Immersive	Interactive technologies	National Museum of the History of Immigration (NMHI)	174 surveys	Comparison experiments	Engaging audiences with interactive technology to ensure a positive learning experience	Pallud (2017)
Immersive	3D tours	Constructivist Learning	565 visitors	Comparison experiments	3D tours boost museum visit intentions by creating engaging and realistic experiences, increasing interest in cultural content	Katz and Halpern (2015)
3D printing	3D printing and design	Cultural history of shoemaking	41 children	Workshop lessons and user feedback evaluation	Using 3D printing to enhance understanding and engagement with young audiences	Turner et al. (2017)
3D printing	3D printing and scanning	Fossil mammal	76 visitors	Workshop and semi-structured interviews	Touchable 3D replicas in museums offer enhanced learning, enjoyment, appreciation, preservation, and interactivity for visitors	Wilson et al. (2017)

create immersive and rewarding learning experiences. Gamification is particularly effective at attracting younger visitors and cultivating curiosity about art, culture, and history (Fig. 16c) (Bozzelli et al., 2019; Cesário & Nisi, 2022; Kiourt, Koutsoudis, & Pavlidis, 2016; Piscitelli & Penfold, 2015). DTTs also facilitate collaborative learning opportunities, allowing visitors to engage in group problem-solving, discussions, and knowledge sharing. VR and MR technologies enable cooperative experiences where visitors can collaborate in virtual or augmented spaces, fostering learning and connections among individuals from diverse backgrounds (Fig. 16d) (Mahmood, Fulmer, Mungoli, Huang, & Lu, 2019; Scavarelli, Arya, & Teather, 2021).

Furthermore, DTTs have expanded educational opportunities beyond the physical confines of museums. Through online platforms and cloud computing, museums can share their collections, educational content, and interactive experiences with remote or underserved audiences, democratizing access to cultural and educational resources (Kuflik, Wecker, Lanir, & Stock, 2015). A study has proposed a mathematical model to analyze visitor experiences shared on a social network within a cultural heritage case study, exploring the influence of shared information on the network and its implications for context-aware profiling and recommendation systems (Fig. 16e) (Cuomo, De Michele, Galletti, & Piccialli, 2015). The British Museum's "Samsung Digital Discovery Centre" is an excellent example of how museums can leverage DTTs to enhance educational programming (British Museum, 2021). The center offers a range of interactive workshops and activities that use cutting-edge technologies such as VR, AR, 3D printing, and digital photography to engage young visitors with the museum's collections. For instance, in the "Sutton Hoo Ship Burial" workshop, participants use 3D printing to recreate artifacts from the ancient Anglo-Saxon site while learning about the historical context and archaeological processes behind the discovery. By integrating DTTs into educational initiatives, the British Museum creates immersive and hands-on learning experiences that spark curiosity, creativity, and critical thinking among young audiences.

These research findings demonstrate how DTTs can enhance learning experiences by improving visitor motivation and satisfaction, stimulating interest in relevant fields such as computer science and AI, scaffolding knowledge construction in informal learning environments, and personalizing learning experiences in line with individual preferences and interests. In addition, interactive technologies and 3D tours can provide positive outcomes for engaging audiences and boosting museum visit intentions. AM can enhance the understanding and engagement of younger audiences and offer enriched learning experiences through touchable museum replicas. Overall, the findings present a comprehensive analysis of various DTT applications leveraged to enhance the educational potential and long-term impact of museum exhibitions, showcasing promising growth in technology-supported learning experiences for visitors of all ages.

3.4. Collecting and analyzing data on visitor experiences

DTTs enable museums to collect and analyze valuable data on visitor experiences, preferences, and behaviors, providing crucial insights for refining exhibitions, delivering better experiences, and anticipating emerging trends. By leveraging technologies such as sensors, tracking systems, and data analytics platforms, museums can better understand how visitors interact with exhibits, navigate the space, and respond to different elements of the experience. This data-driven approach allows museums to identify areas for improvement, such as optimizing visitor flow, adjusting content to better engage audiences, and personalizing experiences based on individual preferences. Moreover, analyzing aggregated visitor data over time can reveal broader patterns and trends, enabling museums to adapt their strategies and offerings to evolving visitor needs and expectations. By establishing a continuous feedback loop between visitor data, insights, and exhibition design, museums can ensure their ongoing success and relevance in the digital age, delivering experiences that effectively captivate, educate, and inspire their audiences.

Table 4 presents an overview of the DTTs for collecting and analyzing visitor experience data from museum exhibitions. It highlights the various methods of data collection, data types collected, data analysis techniques, insights gained from visitor data, and the use of data to improve exhibitions based on the application of technologies such as AI, IoT, Cloud Computing, and immersive technologies. For instance, AI has been employed to collect behavioral and demographic data using low-cost devices and deep neural networks to optimize visitor flow and improve artwork arrangements (Ferrato, Limongelli, Mezzini, & Sansonetti, 2022). IoT and cloud computing have also been utilized to track visitor behaviors and preferences using wireless sensor networks and wearables, allowing museum professionals to redesign exhibitions and provide personalized recommendations to audience (Alletto et al., 2015; Lanir et al., 2017). Moreover, ML, computer vision, and other innovative data analysis techniques can uncover complex patterns and trends in visitor data, providing a comprehensive understanding of how audiences navigate museum spaces and engage with exhibits (Ragusa, Furnari, Battiato, Signorello, & Farinella, 2020).

The integration of DTTs in museums offers unprecedented opportunities for collecting and analyzing data on visitor experiences. Through advanced computer vision and IoT devices, museums can track visitor movement patterns and analyze their behavior, providing insights into their popularity, identifying areas for improvement, and optimizing visitor flow (Fig. 17a) (Centorrino et al., 2021; Lanir et al., 2017). Interactive surveys and feedback collection via smart kiosks and touchscreens allow visitors to provide real-time feedback, enabling museums to gauge visitor sentiments and identify trends or key points of interest. Social media monitoring and sentiment analysis enable museums to gather public opinion, promptly address negative experiences, and improve service quality (Fig. 17b) (Borràs, Moreno, & Valls, 2014; Centorrino et al., 2021). By analyzing the collected data, museums can generate personalized experiences through recommendation systems and AI-guided tours that cater to individual preferences and adapt educational content accordingly (Fig. 17c) (Fararni et al., 2021; Renjith, Sreekumar, & Jathavedan, 2020). Data analysis also plays a crucial role in evaluating the efficacy of DTTs within museum exhibitions by comparing visitor experiences before and after implementation, assessing enhanced accessibility, and analyzing the costs and benefits of museum operations. For example, Emerson et al. conducted an early prediction of visitor engagement at a science museum using multimodal learning analysis (Fig. 17d) (Emerson et al., 2020). The Cleveland Museum of Art's "ArtLens" app is a prime example of how museums can leverage DTTs to collect and analyze visitor data for personalized experiences (Cleveland Museum of Art, 2021). The app uses Bluetooth beacons and indoor wayfinding technology to track visitor movement and preferences within the museum. As visitors interact with exhibits, the app collects data on their favorite artworks, time spent at each piece, and overall engagement levels. This information is then used to generate personalized recommendations, guided tours, and interactive content tailored to each visitor's interests. By harnessing the power of data analytics and machine learning, the ArtLens app demonstrates how museums can create data-driven, customized experiences that enhance visitor satisfaction and loyalty.

Case studies that collect and analyze data on visitor experiences using DTTs offer invaluable insights for museum professionals, allowing them to refine their exhibitions, deliver better experiences, and anticipate emerging trends in museum education and engagement. This feedback loop contributes to museums' ongoing success and sustainability as cultural institutions, proving that integrating these technologies can enable cultural institutions to better capture the dynamics of visitors' interactions with their spaces, preferences, and behaviors. This valuable information can be used to create immersive and personalized experiences that cater to the unique interests and needs of each visitor, leading to an overall improvement in museum exhibitions (Moussouri & Roussos, 2015).

3.5. Managing collections and exhibits

DTTs have revolutionized the management of museum collections and exhibits, offering powerful tools for documentation, preservation, digital restoration, and accessibility. By leveraging high-resolution imaging, 3D scanning, and metadata management systems, museums can create detailed digital representations of artifacts and artworks, serving as valuable assets for preservation and access. These digital surrogates enable museums to monitor the condition of objects over time, detect and address deterioration, and even digitally restore damaged or incomplete items. Furthermore, digitization allows museums to

(a) Personalizing the educational experience for visitors based on their preferences, learning styles and abilities

User interacting with an AI generated character during a health checkup

User learning from an AI generated character resembling an expert giving a lecture

Users becoming AI generated characters resembling historical characters for role playing

(b) Promoting visitors to explore and understand the theme in depth

(c) Gamification to attract the curiosity of young visitors

(d) Promoting visitor collaboration in virtual or augmented spaces

(e) Promoting visitors to share educational experiences

Fig. 16. Examples of enhanced educational features with DTT. (a) User interaction with AI-generated characters for health checks, expert-like learning during lectures, and immersive role-playing experiences as historical figures (Pataranutaporn et al., 2021). Copyright 2021, Springer Nature Limited. (b) Experiential AR learning tools and services are combined online and offline to effectively provide children with information about historical and cultural assets (Lee et al., 2021). Copyright 2021, NSEAD and John Wiley & Sons Ltd. (c) Children utilizing light tables to explore and examine concepts such as transparency, translucency, pattern formation, and color blending (Piscitelli & Penfold, 2015). Copyright 2015, the authors. (d) Creating information sharing and collaborative analysis functions with MR (Mixed Reality) to support users in sharing and analyzing their sensemaking processes together (Mahmood et al., 2019). Copyright 2019, IEEE. (e) An exhibit map displaying the location of smart crickets (in red) and artworks (in blue) (Cuomo et al., 2015). Copyright 2015, IEEE.

highlight their collections online, reaching a global audience and providing virtual access to individuals who may not have the opportunity to visit in person. This expands the educational impact of museums and ensures the long-term preservation of cultural heritage by creating digital backups that can survive physical damage or loss.

Table 5 displays various scenarios where DTTs are applied in conservation and preservation, collection management systems, and digitization and documentation for museum exhibitions. For example, AI-based decision-making models can improve the management of historical buildings, art works, and design works (Bile et al., 2022; Kim & Lee, 2022; La Russa & Santagati, 2021). AM and 3D scanning can be used for digitizing and documenting cultural heritage objects with high-resolution digital images and advanced photogrammetric techniques (Boyer, Gunnell, Kaufman, & McGeary, 2016; García-Molina, López-Lago, Hidalgo-Fernandez, & Triviño-Tarradas, 2021; Kuzminsky & Gardiner, 2012; Menna, Rizzi, Nocerino, Remondino, & Gruen, 2012; Ramm et al., 2022). The combination of IoT, AI, AM, and AR can enhance the architecture of museum systems and monitor artifacts' environmental conditions, leading to improved preservation and restoration (Alsuhly & Khattab, 2018; Konev et al., 2019; Muthanna et al., 2018; Tache, Sandu, POPESCU, & PETRIŞOR, 2018).

One key area where DTTs have revolutionized museum operations is documentation and cataloging, in which AI and computer vision enable efficient management of vast collections with minimal manual intervention, while NLP assists in generating labels and descriptions of artifacts (Fig. 18a) (Jones, Nousir, Everrett, & Nabil, 2023; Konev et al., 2019; Schuettpelz et al., 2017; Smith, 2017). This digital tracking system provides a centralized and organized database that allows quick and accurate retrieval of information regarding specific artifacts, their location, condition, and other relevant details (Fig. 18b) (Alsuhly & Khattab, 2018; Liu, Wang, Qi, & Yang, 2019). This streamlines the overall management of collection and improves the efficiency of inventory tasks. Preservation and conservation efforts have also greatly benefited from DTTs because 3D scanning, modeling, cloud computing, and IoT devices play crucial roles in replicating and monitoring

Table 4
An overview of the application of DTTs in collecting and analyzing data on visitor experiences.

DTT type	Data collection methods	Data types collected	Data analysis techniques	Insights gained from visitor data	Use of data for improving exhibitions	Ref.
AI	Low-cost devices and deep neural networks (i.e., Faster R-CNN)	Behavior and movement track data	Visual Data Analysis	Visitors' track of movement	Personalized services, optimize visitors' flow, improve artwork arrangement	Ferrato et al. (2022)
AI	Mobile devices, replicated to a database via the mobile network	Demographic and location data	Machine learning	Direct link between motivation and visitor routes	Personalized recommendations, exhibit redesign	Moussouri and Roussos (2015)
AI	Wearables, egocentric visual technology	Behavioral data, demographic data, feedback data	Computer vision, machine learning	Visitor behaviors and preferences	Improving the visitor experience	Ragusa et al. (2020)
AI, IoT	Portable devices	Behavioral and location data	Machine learning	Visitors' behavior trajectory, behavior understanding	Visitors flow optimization	Centorrino, Corbetta, Cristiani, and Onofri (2021)
AI, IoT	Proximity detection, mobile devices	Behavioral and location data	Sentiment analysis, machine learning	Visitor behavior and interaction in their space, visitor preferences	Predicting visitor behavior	Martella, Miraglia, Frost, Cattani, and van Steen (2017)
AI, IoT	IoT sensor boards	Location and movement track data	Machine learning	Visitors' behavior trajectory	Personalized recommendations, marketing strategies	Piccialli, Cuomo, Cola, and Casolla (2019)
AI, IoT	Mobile devices, cameras	Onsite physical and Online digital information interaction behaviors	Statistical analysis, machine learning	Visitor interaction behaviors	Effective recommendation in smart environments	Hashemi and Kamps (2018)
AI, IoT, immersive	Sensors, data mining	Feedback and behavioral data	Semantic Analysis, Machine learning	Visitor preferences	Personalized recommendations for museum visits	Torres-Ruiz et al. (2020)
IoT, Cloud Computing	Radio frequency (RF)-based positioning system, wireless sensor network (WSN), sensors	Behavioral and feedback data	Data processing and visualization, statistical analysis	Visitor behavior and interaction in their space, visitor preferences	Exhibit redesign, personalized recommendations	Lanir et al. (2017)
IoT, Cloud Computing	Wearables	Behavioral and location data	Statistical analysis	Visitor behaviors and preferences	Provide visitors with cultural content related to the artwork they are observing	Alletto et al. (2015)

storage conditions. Digital restoration leverages virtual AR and AM to enhance the visual representation of damaged or degraded artifacts without interfering with the original material, thus enriching the visitor experience (Fig. 18c) (Hess, Petrovic, Meyer, Rissolo, & Kuester, 2015; Wilson, Rawlinson, Frost, Hepher, & James, 2018; Xiao et al., 2018).

Furthermore, DTTs streamline the sharing and collaboration of data collection among museum professionals. Previously, the sharing and collaboration of collected data was often hindered by physical distance, limited access, or incompatible systems. However, with DTTs, museum professionals can easily share and collaborate on data collection, regardless of the geographical location. Online platforms, cloud-based storage systems, and shared databases allow professionals to exchange information, research findings, and expertise seamlessly (Fig. 18d) (Chanhom & Anutariya, 2019; DeHass & Taitt, 2018). This facilitates collaborations in research, exhibitions, loans, or conservation projects. Moreover, digital technologies enable the standardization of data formats and metadata, making it easier for different users. The Smithsonian Institution's "3D Digitization Program" highlights the transformative potential of DTTs in managing and preserving museum collections (Smithsonian Institution, 2021). The program aims to create high-quality 3D models of the Smithsonian's vast collections, ranging from ancient artifacts to scientific specimens. Using advanced 3D scanning and photogrammetry techniques, the team captures detailed surface geometry, color, and texture information for each object. These digital models are then made accessible through an online platform, allowing researchers, educators, and the public to explore and interact with the collections in new ways. The 3D Digitization Program facilitates the preservation and sharing of the Smithsonian's collections and enables innovative applications such as virtual exhibitions, 3D printing of replicas, and immersive educational experiences.

Incorporating DTTs facilitates more efficient and effective management of museum collections and exhibits. From documentation and cataloging to preservation and conservation, DTTs provide an ever-growing set of tools and techniques for safeguarding cultural heritage while extending their reach and impact on museum visitors. The future of museum management will likely see increased reliance on these technologies as they evolve and become more accessible.

While each DTT has unique applications and benefits, they work in synergy to revolutionize the museum experience. For instance, AI and IoT can power personalized recommendations and interactive exhibits, while immersive technologies and additive manufacturing can create multi-sensory and tactile experiences. Cloud computing and digital twin technology can facilitate seamless integration and real-time updates across various aspects of museum operations. Together, these technologies enable museums to create holistic, engaging, and data-driven experiences that cater to the evolving needs and expectations of modern visitors.

4. Discussion and perspective

DTTs have revolutionized museum exhibitions for decades, offering immersive and interactive experiences that engage visitors at multiple levels. AI technologies are notably transformative, enabling personalization that caters to visitors' unique preferences and learning styles. Immersion technologies revolutionize museums by bringing exhibits to life and redefining visitor interactions. AM enables physical interactions

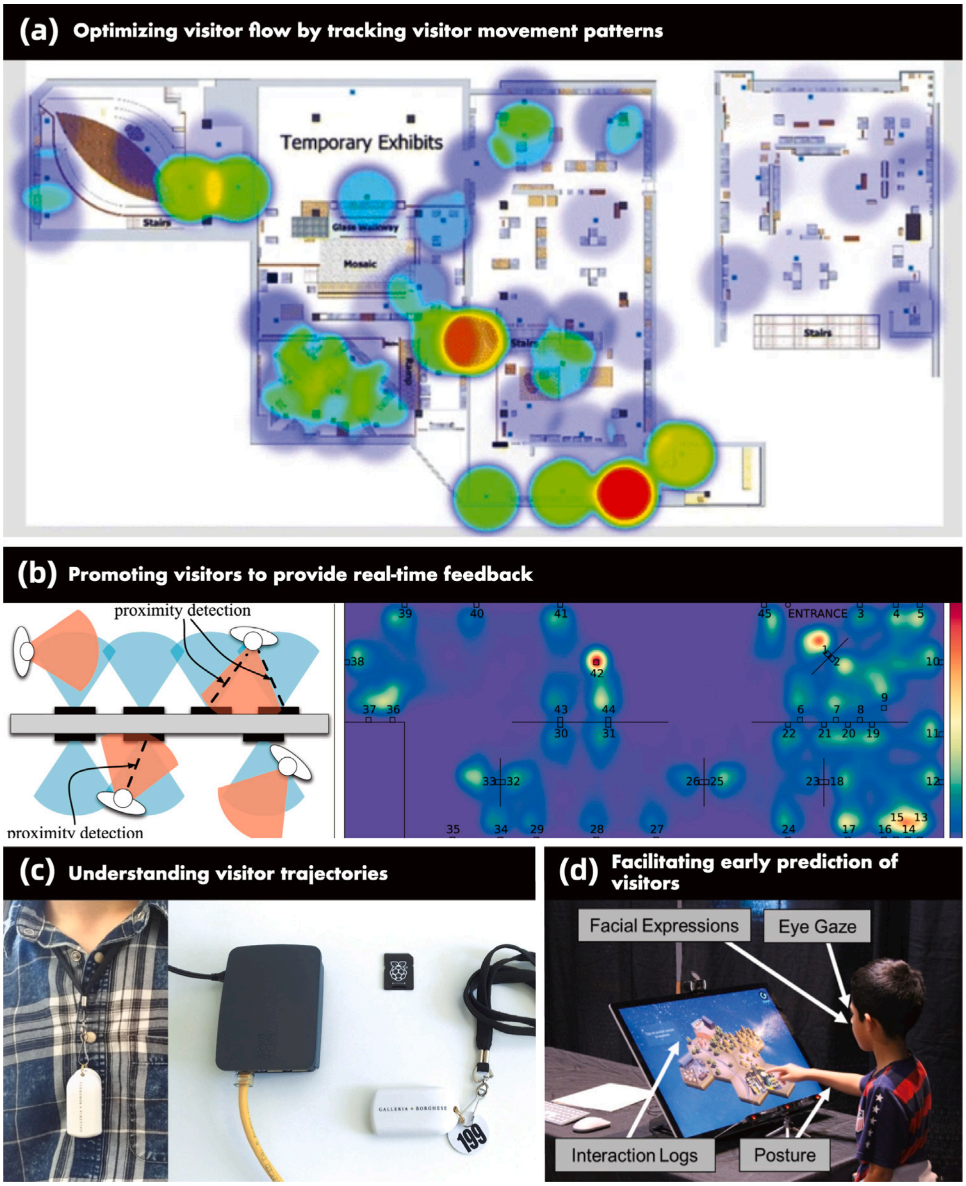

Fig. 17. Examples of visitor experience data collection and analysis functions with DTT. (a) An aggregated view of a heatmap of the visitors' appeal at a museum (Lanir et al., 2017). Copyright 2016, Springer-Verlag London. (b) Detection between mobile devices and anchor points installed on exhibits and heat maps of visitor locations (Martella et al., 2017). Copyright 2017, Elsevier. (c) A radio-based, non-intrusive IoT measurement solution that provides room-level visitor traces (Centorrino et al., 2021). Copyright 2021, the authors. (d) Multi-modal learning analysis for early prediction of visitor engagement in science museums (Emerson et al., 2020). Copyright 2020, Association for Computing Machinery.

with otherwise inaccessible artifacts, while IoT enables seamless integration of smart museums; and cloud computing provides unlimited data storage and processing power. Despite the numerous benefits of DTTs, several challenges and limitations remain. The cost of implementing and maintaining these technologies can be a significant obstacle, especially for small and medium-sized museums that require substantial funding. Fig. 19 depicts a quadrant model mapping the relevance against the required investment for various DTTs in museum exhibitions.

The vertical Y-axis represents the relevance of technology to museum operations, with higher relevancy situated towards the top (French & Villaespesa, 2019). The horizontal X-axis depicts the necessary investment level, with higher investment located towards the right. Technologies such as NLP and Recommendation Systems, which require lower investment but offer high relevance, are located in the upper left quadrant. Although significant in potential, Advanced Robotics can demand substantial investment with lower immediate relevance, placing them in the lower right quadrant. High-investment, high-relevance technologies, such as AR and VR, can be found in the upper right quadrant due to their significant impact and substantial initial costs.

Finally, technologies such as specific features of IoT that require lower investment and might have lower immediacy in relevance are placed in the lower left quadrant. It is essential to note that the locations of each DTT can vary depending on specific circumstances, including the scale, needs, and resources of each museum. In conclusion, Fig. 19 is a strategic tool for museums to navigate their digital transformation journey, aligning technologies with their relevancy and resource availability. It provides a visual representation of the effort and cost associated with technology applications as well as the relevance of the museum in this context, highlighting the importance of the investment required to implement DTTs and their impact on the museum's mission and goals. This figure serves as a reminder that successful technology integration in museums requires a thoughtful

Table 5
An overview of the application of DTTs in managing collections and exhibits.

DTT type	Research field	Types of collectible objects	Collection data types	Methods of data collection	Using data to improve curation	Ref
AI	Conservation and preservation	Historical buildings	3D digital models data	Decision-making model based on machine learning	Helping curators in preservation management	La Russa and Santagati (2021)
AI	Collection management systems	Art works	Museum microclimate variations	Artificial neural network	Enhancing artworks conservation in museum	Bile et al. (2022)
AI	Collection management systems	Design works	Emotional characteristics of the design works	An image retrieval system based on metadata	Enhancing emotional archiving systems	Kim and Lee (2022)
3D printing	Digitization and documentation	The Behaim globe	Geometric, visual and preservation condition data of the Behaim globe	Using high-resolution digital images and automatic photogrammetric techniques	Cultural heritage conservation, visualization and educational purposes	Menna et al. (2012)
3D printing	Digitization and documentation	Cultural heritage objects	Shape and color texture data	A portable 3D digitization system	Cultural heritage preservation and access to digital information	Ramm et al. (2022)
3D printing	Digitization and documentation	Visigothic sculptural heritage	Geometric and visual data	Structured light scanning	Cultural heritage preservation and exploitation	García-Molina et al. (2021)
3D printing	Digitization and documentation	Prehistoric human skeletons	Geometric, visual and detail data	3D laser scanning	Museum conservation, archaeological methods and scientific research	Kuzminsky and Gardiner (2012)
3D printing	Digitization and documentation	Museum specimens	3D digital models data	Generate 3D digital models of museum specimens and archive them through an Internet repository	Museum conservation, research and data sharing	Boyer et al. (2016)
IoT, AI	Collection management systems	Museum artifacts	Artifacts' environmental conditions	IoT and AI, particularly Semantic Web technologies	Enhancing the architecture of the museum system	Konev et al. (2019)
IoT, AR	Conservation and preservation	Museum artifacts	Artifacts' environmental conditions	An end to end system structure	Monitor and indicate any climatic effects	Muthanna et al. (2018)
IoT, 3D printing	Conservation and preservation	Archaeological sites	3D digital models data	UAV technology (a multi-rotor drone), GIS and GPS	Cultural heritage preservation and on-site restoration works	Tache et al. (2018)
IoT	Conservation and preservation	Museum artifacts	Artifacts' environment and their safety conditions	IoT based system	Museum indoor ambience monitoring and control and artifact safety	Alsuhly and Khattab (2018)

assessment of the resources and expertise needed while aligning with the museums' overall objectives. Data privacy and security issues may arise with the implementation of AI and cloud computing, presenting the risks of data breaches and unauthorized access. The misinterpretation or misuse of intricate technologies is another potential limitation. Visitors may also experience digital fatigue owing to overexposure to digital interfaces and media. These challenges must be addressed to successfully integrate DTTs into museums.

4.1. Gaps and opportunities for future research

The current literature on DTTs in museum exhibitions has provided valuable insights into their applications and impacts. However, several areas still require further research attention. One important gap is the lack of longitudinal studies examining the long-term effects of DTTs on visitor engagement, learning, knowledge retention, attitudes, and behaviors. Most research has focused on the immediate impact of DTTs, and future studies should employ pre- and post-visit assessments and follow-up surveys to evaluate their long-term influence. This research could help museums develop more effective and sustainable digital strategies.

Another area that warrants further investigation is the comparative evaluation of different DTTs in various museum contexts. Most of the literature has focused on individual technologies, with limited research comparing their effectiveness for specific exhibition goals, such as enhancing accessibility, interactivity, or information delivery. Future studies could conduct controlled experiments or user testing to assess the strengths and weaknesses of different DTTs, guiding museums in selecting the most appropriate technologies for their needs and audiences. Additionally, as museums increasingly adopt data-driven and personalized approaches using DTTs, there is a need for a more critical examination of the ethical and social implications of these practices. Future research should investigate issues such as data privacy, algorithmic bias, and the digital divide in the context of museum DTTs, using qualitative methods to explore the perceptions, concerns, and expectations of museum professionals and visitors regarding the responsible use of these technologies.

In recent years, LLMs and AI-generated content have begun to significantly impact the design and curation of museum digital exhibitions. The rapid advancements in natural language processing and generative AI have opened up new possibilities for creating engaging, personalized, and interactive experiences for museum visitors. For instance, Trichopoulos et al. demonstrated that museum digital storytelling machines and virtual guides integrated with ChatGPT, a powerful LLM developed by OpenAI, can provide visitors with highly contextualized and informative responses to their queries (Trichopoulos, 2023). However, integrating LLMs and AI-generated content in museum exhibitions raises important ethical and curatorial challenges. As highlighted by Darda et al. there are concerns about the potential biases, inaccuracies, and lack of transparency in AI-generated content, which may undermine the trustworthiness and authenticity of museum narratives (Darda, Carre, & Cross, 2023). Therefore, museums must

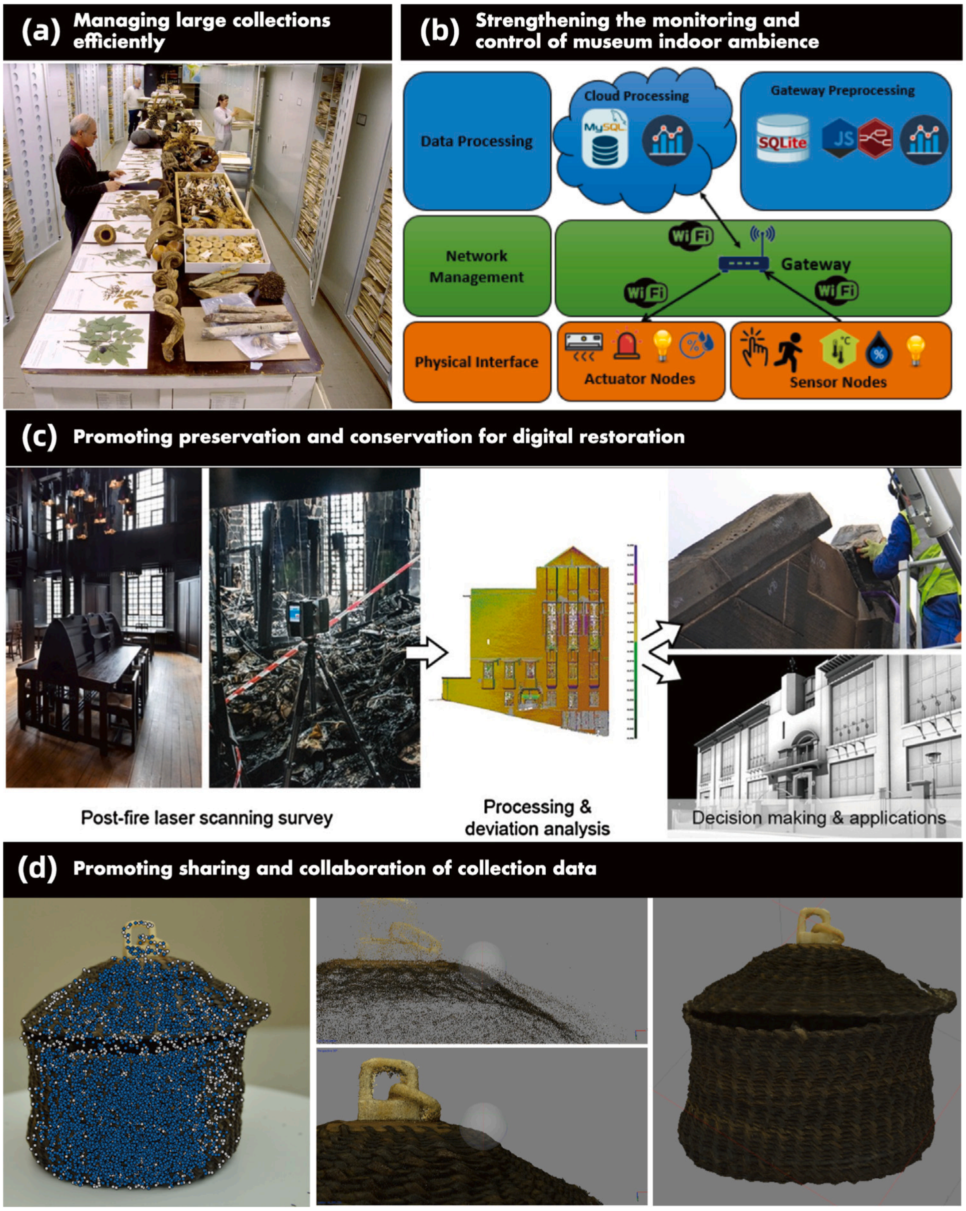

Fig. 18. Examples of managing collections and exhibits with DTT. (a) The digital neural network could distinguish between two similar plant families with an accuracy of over 90% (Schuettpelz et al., 2017; Smith, 2017). Copyright 2017, the authors. (b) Proposed IoT system architecture for monitoring and control of museum interior environment and heritage security (Alsuhly & Khattab, 2018). Copyright 2018, IEEE. (c) Map of the long-term conservation and restoration process of the Mackintosh building using 3D digital documentation (Wilson, Rawlinson, et al., 2018). Copyright 2017, Elsevier Masson SAS. (d) Generating interactive 3D models using 3D modeling and scanning technology effectively helps connect Aboriginal communities with museum collections from different institutions worldwide (DeHass & Taitt, 2018). Copyright 2017, the authors.

develop robust guidelines and best practices for the responsible use of these technologies in digital exhibitions. Future research should systematically explore the application scenarios, impact assessments, ethical considerations, and curatorial practices of LLMs and generative AI in the museum context, providing evidence-based guidance for cultural institutions.

Furthermore, the current literature suggests a need for more interdisciplinary collaboration in designing, implementing, and assessing museum DTTs. Future research could explore innovative methodologies, such as participatory design workshops or living labs, to engage diverse stakeholders in co-creating and evaluating DTT solutions. This approach could foster more user-centered and context-sensitive digital innovations in museums. Additionally, while some studies have touched upon the financial and managerial challenges of implementing DTTs, there is scope for more in-depth research on the economic and organizational factors influencing their adoption and sustainability. Future studies could employ cost-benefit analyses, business model canvases, or organizational change frameworks to investigate how museums can effectively allocate resources, build digital capacities, and align DTTs with their strategic goals and values.

By addressing these specific gaps and pursuing targeted research questions using appropriate methodologies, future studies can contribute to a more comprehensive and nuanced understanding of the role and impact of DTTs in museum exhibitions. This understanding can inform evidence-based strategies and policies for the successful and sustainable integration of digital technologies in the cultural heritage sector, ultimately enhancing the visitor experience and supporting the preservation and dissemination of cultural knowledge.

4.2. *Practical implications and recommendations*

Based on the findings of this systematic review, we propose several practical recommendations for museums seeking to effectively integrate

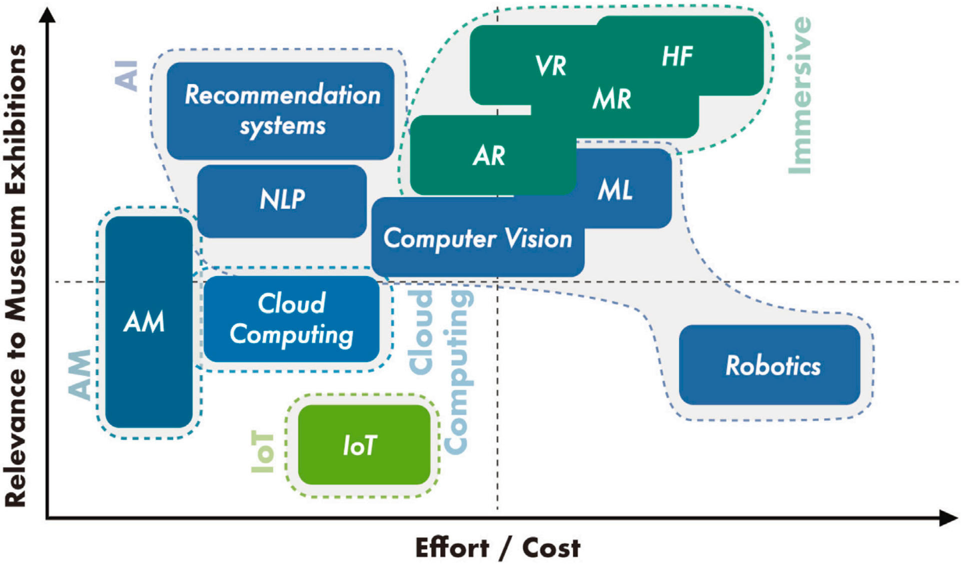

Fig. 19. The effort and cost of technology applications and the relevance of the museum exhibitions.

DTTs into their exhibitions. Primarily, museums should establish a clear digital strategy that aligns with their overall mission, goals, and target audiences. This strategy should prioritize DTTs that enhance visitor engagement, accessibility, learning, and experience while considering the institution's available resources and long-term sustainability.

To ensure the successful development and evaluation of digital initiatives, museums should foster interdisciplinary collaboration among professionals from various fields, including curators, educators, designers, technologists, and researchers. This collaborative approach enables the creation of well-rounded and effective DTT solutions that address the needs and perspectives of different stakeholders. Additionally, museums must invest in building their staff's digital skills and competencies, as well as the necessary technological infrastructure, through targeted training programs, hiring specialized personnel, and allocating adequate resources.

Actively involving visitors and other stakeholders in designing, implementing, and evaluating DTT initiatives is crucial for creating user-centered and engaging experiences. Museums can achieve this through participatory methods such as co-design workshops, user testing, and community outreach programs. Furthermore, prioritizing accessibility and inclusivity should be a key consideration when integrating DTTs. This involves adhering to universal design principles, providing alternative modes of interaction and interpretation, and ensuring that digital content is perceivable, operable, understandable, and robust for all users, regardless of their abilities or backgrounds.

As museums increasingly rely on digital technologies, it is essential to establish robust data privacy and security protocols. This includes developing clear data governance policies, obtaining informed consent from visitors, anonymizing personal data, and implementing appropriate technical and organizational safeguards to protect sensitive information. Finally, museums should continuously monitor, assess, and improve their DTT initiatives through quantitative and qualitative evaluation methods. The insights gained from these evaluations should inform iterative refinements and adaptations to ensure that the digital offerings remain relevant, effective, and engaging over time. While these recommendations provide a general framework for success, it is important to recognize that museums must tailor their approach to their specific contexts, resources, and goals, as there is no one-size-fits-all solution for navigating the challenges and opportunities associated with DTT integration in the museum sector.

The digital transformation of museums is an inevitable trend, and the application of new technologies brings unprecedented opportunities for enhancing visitor experiences, expanding service reach, and optimizing operational management. However, as museums embrace technological changes, they also face multiple challenges, including financial investment, talent gaps, digital divides, and intellectual property rights. The digital transformation has profound and complex impacts on museums' operation models, discourse power, and social roles. In the future, museums need to explore how to find a balance between the virtual and the real, between entertainment and enlightenment, and between digitalization and the humanistic spirit. The goal of museum digital transformation should not be limited to technology application but should focus on enhancing cultural resilience. By combining artificial intelligence with human wisdom, museums can become a bridge connecting the past, present, and future, linking different cultures and communities and providing intelligent insights for the sustainable development of human society. This requires collaborative efforts from museums, the technology industry, academia, and the public.

5. Conclusion

Over the last decade, DTTs have significantly affected the landscape of museum exhibitions, compelling a shift towards more immersive, inclusive, and personalized visitor experiences. This systematic review comprehensively examines the current state of technology-enhanced museum practices, focusing on the implementation and impact of AI, immersive technologies, AM, IoT, and cloud computing in museum exhibitions. Adopting these emerging technologies offers unique opportunities for reimagining exhibitions and services. They enable the creation of engaging and interactive exhibits, improve accessibility to diverse groups, enhance educational opportunities, and increase efficiency in collection management. Their application provides empirical data, offering immediate and long-term insights into visitor behaviors and preferences. Integrating DTTs with museums holds significant potential for deeper engagement and understanding of exhibited content and personalized and interactive learning experiences.

The current trend suggests that museums will continue expanding their use of digital technologies in response to visitors changing demands and expectations, as well as the broader societal context. This shift encompasses the technological transformation of museum practices and rethinking traditional roles, functions, and relationships within the cultural heritage sector. As museums journey towards digital transformation, they face various technological, human, and organizational challenges. Future research should explore these challenges and ways to maximize the benefits of DTTs while minimizing potential risks and ethical considerations.

The digital transformation of museums aligns with the agenda of many international policies and initiatives to promote accessibility, inclusivity, sustainability, and the preservation and enrichment of cultural heritage. The findings of this review have implications for museum professionals, policymakers, technology developers, researchers, and educators in cultural heritage and museum studies. They provide a timely perspective of the pandemic-induced accelerated digital shift and contribute to advancing the academic discourse and practices in technology-enhanced museum exhibitions.

The systematic review conducted in this article contributes significantly to the existing literature on the digital transformation of museums and cultural heritage institutions. By offering a comprehensive analysis of the applications, benefits, challenges, and future directions of DTTs in museum exhibitions, this review provides valuable insights into how these technologies transform the roles, practices, and impacts of museums in the modern era. The findings and recommendations presented in this article can serve as a foundation for future research, policy development, and practical implementation strategies to leverage DTTs to create more engaging, inclusive, and sustainable museum experiences for diverse audiences.

This review makes several unique contributions to the field. First, it offers a systematic and up-to-date synthesis of the literature on DTTs in museum exhibitions, covering a wide range of technologies, contexts, and perspectives. This comprehensive approach provides a holistic understanding of the current knowledge and practice in this rapidly evolving field. Second, the article presents a conceptual framework that captures the multiple dimensions of DTT integration in museums, including design, accessibility, education, visitor experience, and management. This framework is useful for researchers and practitioners to navigate the complexities of digital transformation in the museum sector.

Another key contribution of this review is the identification of major challenges, opportunities, and best practices for implementing DTTs in museums. Drawing on empirical evidence and practical insights from case studies, this article provides a nuanced understanding of the factors that influence the successful adoption and integration of these technologies in different museum contexts. Moreover, the review proposes a research agenda highlighting critical areas for further investigation, such as the long-term impacts, comparative effectiveness, ethical implications, and participatory development of DTTs in museums. This agenda can guide future studies and collaborations to advance knowledge and practice in this field.

Importantly, this article bridges the gap between theory and practice by offering actionable recommendations for museum professionals, policymakers, and technology providers seeking to effectively leverage DTTs for enhancing museum experiences. These recommendations are grounded in the systematic review findings and provide practical guidance for navigating the challenges and opportunities associated with digital transformation in the museum sector. By situating this review within the broader landscape of museum studies, digital heritage, and human–computer interaction research, the article contributes to advancing interdisciplinary knowledge and collaboration in the field. It also emphasizes the need for more critical, reflexive, and participatory approaches to the design, evaluation, and governance of DTTs in museums, ensuring that these technologies are culturally sensitive, socially responsible, and aligned with the public interest.

In conclusion, this systematic review highlights the transformative impact of DTTs on museum exhibitions. By enabling immersive and interactive experiences, enhancing accessibility and inclusion, improving educational potential, providing visitor insights, and facilitating collection management, these technologies are redefining the role and relevance of museums in the digital age. However, successfully integrating DTTs requires addressing various technological, organizational, and ethical challenges. Future research should explore innovative solutions, best practices, and collaborative approaches to harness the full potential of DTTs in the museum sector. As museums navigate the digital landscape, strategic adoption of DTTs will be crucial in engaging diverse audiences, preserving cultural heritage, and ensuring the sustainability and resilience of these institutions in the 21st century and beyond.

CRediT authorship contribution statement

Jingjing Li: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Xiaoyang Zheng:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Ikumu Watanabe:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Yoichi Ochiai:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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