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RESEARCH ARTICLE

Evaluation of an HMD-Based Multisensory Virtual Museum Experience for Enhancing Sense of Presence

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ABSTRACT Advancements in digital technology have enabled the production of head-mounted display (HMD) -based digital cultural heritage virtual reality contents that provide immersive experiences through audiovisual interaction in a three-dimensional virtual space. However, these contents do not support tactile sensations and only provide audiovisual information using a controller, which limits users' perception of cultural assets. In this study, we propose an HMD virtual reality-based multisensory digital cultural heritage content that increases the feeling of presence by giving tactile sensations in addition to auditory and visual senses. We present a virtual museum content that implements dummy objects and virtual objects that are 3D printed by high-precision scanning of artifacts and connects their locations with sensors so that users can touch and move them in various directions to feel their shape and size and enhance the sense of reality. Thirty-two participants were recruited to conduct quantitative and qualitative evaluations on realism, immersion, and preference, to compare the proposed multisensory method with the traditional audiovisual method. The experimental results showed that the HMD-based multisensory virtual museum enhanced realism, as users can naturally touch the dummy and feel the presence of artifacts through bare-hand interaction and that immersion and preference are enhanced through the novel multisensory experience.

INDEX TERMS HMD virtual reality, immersive technologies, presence technologies, sense of touch.

I. INTRODUCTION

Recently, cultural heritage centers and museums have embraced new technological changes to improve public awareness regarding history and culture and effectively communicate information regarding the artifacts on display [1], [2]. Instead of the traditional collection-oriented and one-sided exhibition method, latest technologies are being used to provide visitors with a more active and immersive experience of the artifacts [3], [4]. Moreover, efforts are being made to adopt new experience-oriented exhibition methods [5], [6], [7], [8].

In the UK, the British Museum is displaying Bronze Age artifacts as immersive virtual reality (VR) content to help visitors understand the past environment across time and space [9]. The Louvre in Paris has implemented Mona Lisa VR content to provide visitors with an immersive experience that enhances their understanding of the original painting [10], and the Smithsonian's National Museum of Natural History in the United States offers educational VR content on ways to protect the natural ecosystem of coral reefs through a VR headset [11]. Thus, museums are making efforts to combine the traditional concepts of collecting, preserving,

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researching, educating, and exhibiting archaeological materials with VR technology to showcase various exhibition techniques. Further, they are developing spaces that provide cultural enjoyment to visitors [12], [13]. However, most of these museum VR contents rely on an audiovisual experience and exclude other senses [14], [15]. Particularly in museums, where touching artifacts is restricted for preservation and safety reasons, interacting with digital cultural heritage content using controllers is not natural; moreover, the lack of the sense of touch leads degrades the sense of presence and immersion in the virtual space, thus reducing interest in the content and limiting the educational value of the artifacts. Art theorists such as Johann Gottfried Herder have argued that viewing artifacts only with the eyes is insufficient, and that the beauty of the form must be felt with our various senses [16].

In the 17th and 18th centuries, visitors in museums were allowed to hold and touch the objects on display [17], [18]. However, as the popularity of museums increased in the 18th and early 19th centuries, the number of visitors also increased; consequently, the need for care and conservation of the artifacts resulted in the restriction of physical contact with the artifacts [19], [20]. Audiovisual-oriented exhibitions with limited access to museum artifacts continue to this day [21]. However, the visitor's sense of touch is known to be crucial in perceiving and understanding the inherent material properties of the artifacts [22]. Hence, various methods have been studied to provide accessible tactile experiences while preserving the uniqueness of the artifacts [23], [24], [25].

User experience experiments conducted in prior research that compared the audiovisual viewing of an artifact to touching a replica of the original artifact while viewing it have shown that the latter is useful in enhancing the understanding of the artifact [26]. Reportedly, the users gained enhanced knowledge of the artifact when a replica of the artifact was attached to the controller that allowed the users to interact with and touch the artifact in a virtual environment through a system connection [27].

Three-dimensional (3D) -printed artifacts have advantages in terms of time and cost of production. Therefore, museums are currently using such artifacts in their exhibitions, thereby providing visitors with an experience that allows them to touch the artifacts directly. Although the 3D-printed replicas appear similar to the actual artifact, the visual representation of detailed colors and textures is limited. Moreover, the 3D-printed dummy attached to the controller in the virtual environment is different from the original artifact, and the tactile sensation is not accurately transmitted.

Therefore, in the head-mounted display HMD-based multisensory VR approach proposed in this study, the actual artifacts are digitized with high-precision scanning data, the visual effects are presented through 3D data in the original form, and the dummy fabricated using 3D printing is connected to the system by attaching sensors to provide tactile interaction, such as touching the artifacts directly with the user's bare hands in the virtual environment. In particular, the proposed technology excludes the controller from the virtual environment content and applies bare-hand recognition technology to simultaneously control the virtual object of the artifact and the dummy object in the real environment. Consequently, the user can move the artifact up and down, left and right, and rotate it with six degrees of freedom (DOF) in real time, allowing the user to view the artifact in detail using natural interactions through sight, sound, and sense of touch. Participants were recruited to verify the application of multisensory technology to virtual museum contents, and the proposed multisensory museum contents were compared and evaluated with the existing audiovisual HMD-based virtual museum contents to analyze the correlation between enhancing the sense of presence and increasing immersiveness and to identify preferences based on the difference between the two viewing methods.

The contributions of this study are as follows.

- This study proposes an HMD virtual reality-based multisensory digital content for understanding a heritage object that provides an immersive experience by giving tactile sensations in addition to auditory and visual senses.
- In addition, this study proposes multisensory virtual museum contents, wherein users can use their bare hands for natural interaction with a 3D-printed dummy object without controllers in an HMD-based VR environment.
- The proposed virtual museum visit will provide a new multisensory experience for visitors to freely manipulate digital artifacts enhancing their understanding of the artifacts' characteristics.

The remainder of this paper is organized as follows. Section II reviews the existing research and methods applied to visual and auditory-dominated HMD virtual reality technologies and cultural heritage relevant to our research. Section III presents the proposed approach for multisensory-based virtual museum content. Section IV reports on the experiments, and Section V provides a comparative analysis of the existing virtual reality content and the proposed virtual museum with state-of-the-art methods. Subsequently, in Section VI, we discuss the sense of presence, immersion, and preference. Finally, Section VII concludes this study.

II. RELATED WORK

A. HMD-BASED VR

VR technology was commercialized in 1994 as a video output device with a three-axis gyroscopic sensor worn on the head like a pair of glasses and presented an HMD with 3D graphics of a virtual space [28].

By connecting to a computer, HMD VR technology can present lifelike visual graphics and virtual perception to create a strong sense of immersion [29]. The prototype of the first VR technology was a machine called Sensorama, designed by Morton Heilig in 1962, which had audio and visual display on a 3D screen, along with two prototype devices based on

TABLE 1. Modern HMD VR devices.

HMD	Meta Quest 2	HTC VIVE Pro	PlayStation VR2
Product			
Resolution	1832 x 1920	2880 x 1600	2000 x 2040
Scanning rate	90Hz	90 Hz	120Hz
Sound	3D position-based audito	High impedance audio	Tempest 3D AudioTech2
Weight	772g	600g	560g
Controller			
Sensation	Sight, Hearing, controller vibration haptic	Sight, Hearing, controller vibration haptic	Sight, Hearing, controller vibration haptic & HMD vibration haptics

multisensory technology that provided multiple senses such as touch and smell, for example, the perception of blowing wind, which reimagined the immersive environment [29]. Subsequently, in 1966, it was used in virtual flight training in the U.S. Air Force. Next, the technology was developed for military use. An HMD equipment that could be worn on the head instead of being fixed on the desk was designed; however, it had to be supported by connecting it with a string to the ceiling as it was heavy [30]. Research on systems for multisensory applications in virtual environments has been ongoing since the 1960s [31]. In the context of cultural heritage, a multisensory platform has been developed for interacting with small artifacts using VR technology, and some studies have demonstrated the capability to touch artifacts using another haptic device [32]. Haptics has also been used to provide the multisensory experience of seeing, hearing, and touching a bent virtual musical instrument through the interactive sense of touch [30]. One such haptic device, the PHANTOM Omni, implements force feedback in conjunction with the haptic technology to deliver multisensory experiences in VR. However, the haptic interface controller is fixed and cannot be moved, thus limiting its ability to convey a realistic sense of presence.

Recently, with the development of VR HMD-based technology, new products are being released. Table 1 details modern HMD VR devices and their features. In particular, the latest VR HMDs have improved resolution and are light weight with applications being developed with easy to operate controllers, thereby allowing users to experience immersive virtual environments with ease and convenience [33].

Meta's VR device, Quest2, is the latest in a long line of HMDs from global companies. It has a resolution of 1832 × 1920 pixels per side and a wide field of view (FOV), and it uses touch controllers in both hands with location-based audio. Additionally, it has hand-tracking technology that can recognize bare hands. However, it needs further improvement, as it does not work with tactile content but rather uses controllers to interact with objects. Upcoming products will have displays with 1.0 acuity clarity and eye tracking, complemented by variable focus and lens aberration adjusters [34]. HTC VIVE Pro 2 and Sony's PlayStation VR2 are other commercially available products. HTC VIVE Pro 2 offers a resolution of 5K and an FOV of 120°, along with high-quality sound and controllers [35]. Sony's PlayStation VR2 offers four times the resolution of its predecessor, with two 2000 × 2040 OLED displays delivering 4K HDR video at up to 120 fps [36]. The latest VR products are based on the audiovisual technology. In addition to the audio and visual senses, the sense of touch is limited to using a controller to stimulate vibrations in the hand, which is highly insufficient in providing a multisensory experience [35]. The latest HMD-based technologies are attempting to stimulate the five human senses; however, these technologies focus on the audio and visual aspects and use controllers for immersion. Because humans perceive and understand information with all five senses, we can feel the sense of presence when experiencing virtual environments that are provided with multisensory information without any sense of heterogeneity and can thus gain an experience beyond a simple VR experience [15]. Therefore, other senses such as touch, smell, and taste must be included in virtual environments, and effective research is required to maximize the sense of presence and enable users to feel all five senses with multisensory information beyond the audiovisual experience delivered by the current VR technology.

B. VR TECHNOLOGY IN CULTURAL HERITAGE

Digital cultural heritage, a concept that emerged with advancements in digital technology, initially focused on the 3D virtual reconstruction and restoration of cultural heritage, and on implementing a virtual environment with technology based on photogrammetry. Related studies digitized museum collections and created virtual museums to navigate in a virtual space using HTC VIVE headsets [37]. A study on traditional cultural bell ringing used laser scanning and photogrammetry to implement a metaverse platform using Oculus Quest2 to move around a virtual museum and interact with exhibits [38]. Another study used a 360° camera to capture 2D high-resolution images of murals in temple environments and then used these images as tangible data for creating virtual tours of temples [39]. A virtual reconstruction of the ruins of the Forum of Augustus in Rome and Italy, and an environmental storytelling and learning-by-doing approach were implemented in a VR game [39]. An immersive HMD-based virtual tour interactively explored a Greek heritage site, and the virtual tour enhanced interactivity [40].

In the field of cultural heritage analysis and diagnosis, a study on VR platforms for site analysis developed a prototype of a technologically-reproduced archaeological site in an HMD virtual environment [41]. Additionally, a study on the remote diagnosis of cultural assets in a virtual environment allowed site managers to upload information on the status of architectural, cultural assets to perform remote diagnosis [42]. Although these studies have contributed to increasing access to cultural heritage and effectively delivering relevant information through realistic, immersive environments, they do not satisfy the human experience related to the five senses because they only provide simple information relying on sight and sound. Thus, imparting a deep understanding and rich experience of cultural heritage to the visitors is challenging, which limits the ability of these studies to fully convey the value of cultural heritage.

Humans use multiple senses to perceive the world, and these senses play a crucial role in perceiving and understanding objects. For digital cultural heritage content, visitors must be provided with an even distribution of sensory stimuli. Among the five human senses, the sense of touch can provide additional information alongside visual information regarding objects in the environment, thereby helping users understand and interact with artifacts in a virtual environment [43]. Therefore, the absence of technological delays between sight, sound, and touch can eliminate awkwardness and increase the sense of presence [15], [44], [45]. For example, the SCHI sky Lab conducted a study at the Tate Britain Art Gallery in London, UK, on ways to design artistic experiences considering multisensory stimuli, and found that visitors reported higher levels of immersion when viewing art that combines touch, sight, and sound compared with taste and smell [46].

The University of Bonn, Germany, conducted a user experience study comparing the interaction of 3D printed tangible objects attached to the controller of the VIVE HMD with digital visualizations of tangible cultural objects to a keyboard and mouse [27]. The results showed that the tactile sensation of 3D printed tangible objects attached to the former controller had a positive effect on enriching the user's experience and increasing immersion. However, it is different from the size of the original tangible as the tactile 3D printed tangible is attached to the controller, and it is limited in conveying the realism of touching the tangible as the user's hand is not visible in the virtual environment when viewing. In virtual environments, the user's hands are important tools for experiencing a realistic and immersive environment when interacting with virtual objects. Hence, some studies have used 3D modeling of visually visible hands [36], [47].

Multisensory learning studies on cultural heritage VR technologies such as these have shown that when more senses are provided for acquiring new information, the memory of the object after the experience is better and the understanding of the object is greater [48], similar to how exhibitions and experiences enhance the learning experience.

Research on the application of multisensory technologies suggests that the provision of multisensory technologies that deliver information to the five human senses enhances visitors' understanding of cultural heritage. Thus, in the case of VR content in museums, to better understand and learn cultural heritage, a better understanding of the value of artifacts and a richer experience when experiencing digital cultural heritage can be imparted through interactions that provide multiple senses, rather than when only audio and visual senses are provided. In particular, multisensory cultural heritage experiences can be a highly effective way of experiencing artifacts in a virtual environment.

III. METHODOLOGY

This section details the research and development methodology for the proposed content. First, we describe the overall framework of the multisensory content design for the implementation of immersive equipment and modules that provide tactile sensations including vision and hearing. Second, we describe the system modules that allow multisensory interaction and the system that is created by connecting virtual 3D artifacts and 3D-printed dummy objects. Third, we describe a technical method of virtually restoring ceramic artifacts through high-precision scanning to create the virtual museum environment. Finally, we describe the development of virtual museum content by integrating the multisensory fusion module system and virtual museum 3D asset data in Unity 3D. Thus, this study describes the research and development process of a multisensory virtual museum that provides the sense of touch as well as audio and visual senses.

A. DESIGN OF MULTISENSORY VIRTUAL MUSEUM CONTENT FRAMEWORK

As an important part of the HMD-based virtual museum content requiring multisensory element technology and connection with HMD devices, we divide the system module into two parts: a module that recognizes and tracks both hands of a user, and a sensor module that is linked with the 3D data of the artifact prototype and printed dummy object. These two modules are connected with VIVE HMD devices, and the entire system is integrated and connected in Unity 3D as a system that interacts with the user through visual, auditory, and tactile senses.

The first technical part of the multisensory fusion module is the two-hand motion recognition module capable of recognizing the user's hands. The 3D virtual hand is expected to provide the same sensation as the user's physical hand using realistic 3D modeling through bare-hand recognition.

The second module, the real-time interlocking of virtual objects and dummy objects, digitizes the size and texture of the original artifacts through high-precision scanning to form content data, prints them with scanning data, and uses them as dummies. Further, sensors are attached to the printed artifact dummies and are connected with the system to ensure that the virtual data and dummies can move freely in all directions. The two modules are connected to the system to allow users to freely move and touch the artifacts with their bare hands, thus enabling a multisensory fusion system module.

The 3D environment configuration required for the internal environment of the virtual museum content is designed to use the 3D modeling data of general museum exhibit materials or 3D assets created by 3D scanning and retopologizing the materials. The artifacts are organized into a database and can be used in combination with audiovisual information along with metadata and 3D asset models of the artifacts. The audiovisual information includes text, image, video, and audio information regarding the artifact, presented through the information window of the UI. In this system configuration, the virtual museum for viewing the artifacts in a virtual environment is configured such that the dummy artifact can be used by scanning the actual experimental space. Thus, users can intuitively interact with the artifact through tactile senses, in addition to audio and visual senses, while experiencing the museum environment as in real life.

Any 3D environment used in the virtual museum can be restricted to a fixed location, and the virtual objects associated with the dummy can be placed in any one of these environments. This allows the user to move around within a specific area of the virtual museum.

The system is designed to allow users to modify their position during the museum experience by allowing them to be aligned with a calibration system when they needed to reposition themselves. Therefore, when users view the exhibition, the dummies exist in predetermined locations and can be touched in a virtual space, thereby allowing the users to feel their presence while focusing on viewing the artifacts. The virtual museum is designed to provide a multisensory experience of the artifact information, which has been lacking in exhibition content to date. The overall HMD-based multisensory virtual museum framework design is depicted in Fig. 1.

B. MULTISENSORY FUSION SYSTEM MODULE

To realize a multisensory interaction environment system, we set up a virtual environment connected by sensors using VIVE Pro Eye HMDs, four Base Station 2.0, and a VIVE Tracker. In the built environment, the VIVE HMD and controller can recognize the user's location information. To implement a bare-handed interaction system without a VIVE controller in a virtual environment, we tested Leap Motion and Kinect, which precisely track the finger and hand movements of two users, and used Leap Motion for our purpose. We applied the Leap XR Service Provider script to connect the Leap Motion sensor to the HMD VIVE device and implement the basic setup for tracking hand gestures with Leap Motion in the Unity3D development environment. Next, we set up objects for each palm and finger and assigned their respective position and rotation values to the script to apply to Leap Motion. Instead of using the 3D hand model provided by Leap Motion, we created realistic virtual 3D user hand data and used photo textures to create and apply realistic virtual hands.

Additionally, to move the joints of the hand model, we made the bones in the form of rhythmic joints and rigged them with the 3D model to enable joint movement of the hand model. The 3D hand modeling was then prefabricated in Unity3D, applied to Leap Motion, and implemented as a two-handed motion recognition system module connected to the immersive VIVE HMD, as shown in Fig. 2.

Next, the system module for real-time linkage of virtual objects and dummy objects was developed based on Unity Engine 2020.2.5f1. To track the VIVE HMD, we installed the SteamVR Plugin and applied a script to track the tracker sensor based on XR Plugin Management and Open VR provided by Unity 3D to enable tracker tracking in the HMD-based virtual environment. Moreover, 3D-printed dummy objects and 3D artifacts in the virtual environment were interlocked to provide a tactile experience when touching the dummy. We attached the tracker sensor to the dummy object in the VIVE default environment previously built by us, and the position of the sensor could be located in the Unity 3D development environment.

The sensors attached to the dummy were aligned to the same position as that of the 3D model, and the high-key structure was included in the 3D model within the system and connected to the program for testing. Generally, because the sensor and dummy model have different center axes, they do not match when rotated, depending on the position, and the dummy and 3D model are distinct. Thus, herein, we implemented the sensor and dummy model with the same center axis by aligning the axes in the program to ensure that the 3D model and dummy were set to be identical in the VR environment, and the 3D model was interlocked without texture at the same time when the user held and moved the dummy. Evidently from Fig. 3, the same-scale 3D model of the pottery moves in real time with the dummy.

C. BUILDING 3D ENVIRONMENTS FOR MUSEUMS

The 3D environment for realizing the virtual museum content was built by creating 3D models of the artifacts and the internal environment of the virtual museum. The artifacts to be viewed in the virtual museum were those that provide the sense of touch and could be touched by connecting the multisensory fusion system module. The selection criteria were as follows. First, artifacts that are not excessively large or excessively small were considered so that users can touch them with their hands, hear about them, and observe them in various ways. Second, artifacts exhibited in real museums having high historical, artistic, and academic value were selected, rather than artifacts that were unfamiliar to people, to ensure that the exhibition environment for the virtual museum was similar to that of a real museum. Therefore, the final selected artifacts were ceramics; specifically, we selected Goryeo celadon and Joseon white porcelain ceramics that have historical value and can provide meaningful information. The Goryeo inlaid celadon, designated as a national treasure, is a celadon inlaid meteorological vase with a height of 42.1 cm, mouth diameter of 6.2 cm, and base diameter of 17 cm; it was made in the 12th century. The small, low, and slightly open mouth of the vase gives a glimpse of the excellence of Goryeo ceramics and the creativity of the Goryeo people. Designated as a Joseon white porcelain treasure, the white porcelain jar with openwork peony and scroll design in underglaze cobalt blue measures 26.5 cm in height, 14.3 cm in mouth diameter, and 16.5 cm in base diameter. Dating from the 18th century, it is characterized by vine patterns painted in celadon and peony flowers carved in an openwork technique. The two pieces are on display at the Gansong Museum of Art and the National Museum of Korea, respectively, both of which are among the country's

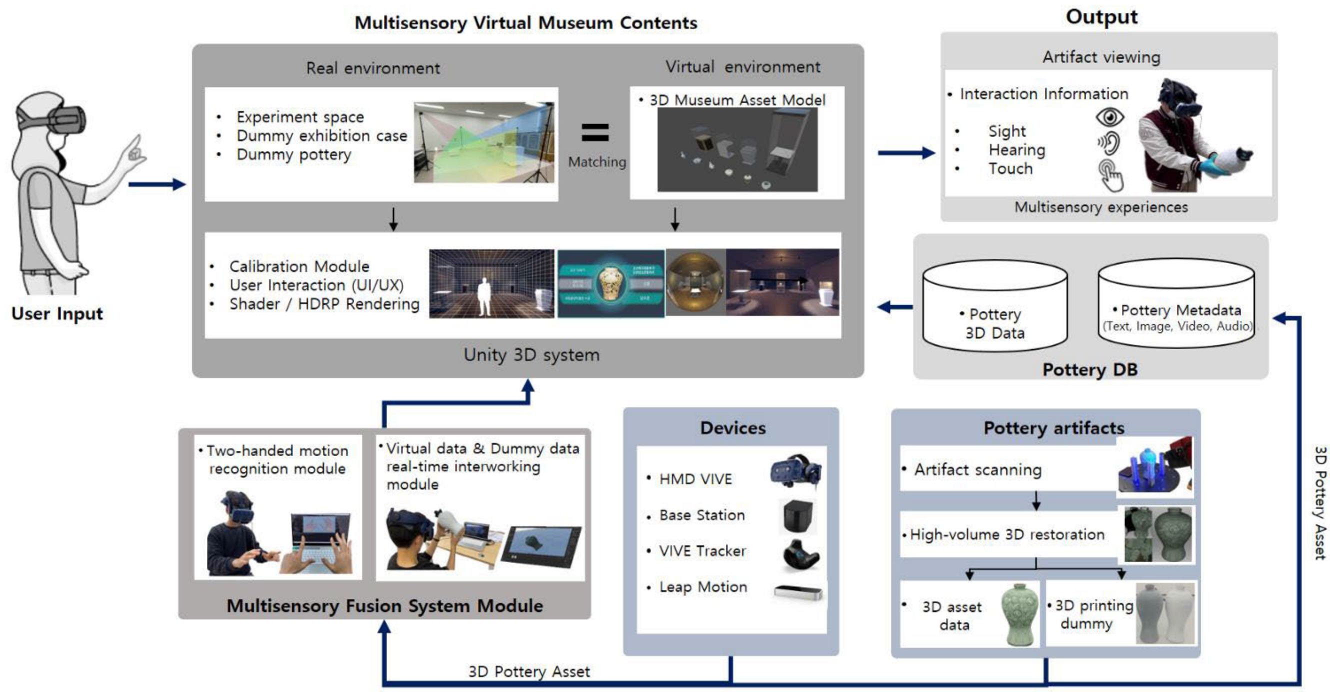


FIGURE 1. Proposed framework for an HMD-based multisensory virtual museum experience.

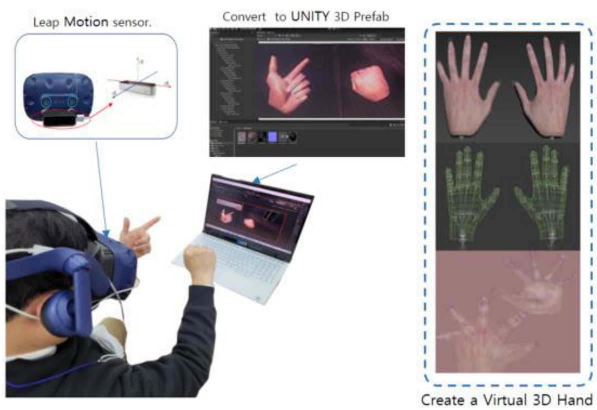


FIGURE 2. Illustration of HMD-based two-hand motion recognition system module.

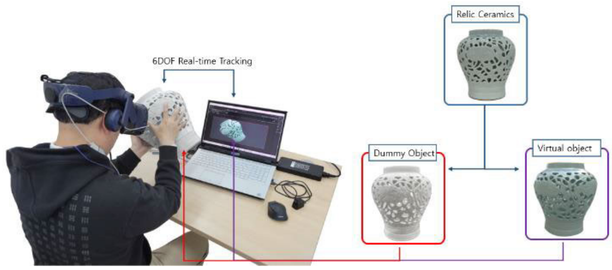


FIGURE 3. Illustration of virtual object and dummy object real-time interworking module.

leading museums. The selected ceramics, illustrated in Fig. 4, were made to resemble the actual artifacts by professional potters, then scanned using high-precision ATOS Compact Scan equipment, and digitized into 3D point cloud data. After postprocessing, denoising, aligning, and merging, they were created as high-capacity 3D meshes and then retopologized in 3D MAX and ZBRUSH to make them usable as virtual museum content.

Thus, 3D models were obtained with a controlled number of modeling faces, and the textures were photographed and made into high-quality images to create 3D model assets that could be used in a virtual environment. The high-capacity scanned 3D models were then printed on an HP Jet Fusion 580 3D printer to create dummies. The process is illustrated in Fig. 4. Next, we scanned the real-world space to realize the interior environment of the virtual museum in 3D. The actual experimental space was rectangular with a width of 2.5 m, length of 6.5 m, and height of 2.6 m, and the point cloud data were created by scanning all four sides with a wideband FARO scanner. The extracted scanning data were postprocessed with noise removal and data merging to create a high-capacity 3D mesh data. To optimize the large amount of scanned data, drawings were created with the mesh sketch function in Geomagic Design X to create a 3D surface with the same size as the actual experimental space. Subsequently, the data were imported as an FBX file and recreated as a 3D polygon model in 3D MAX with the same width and height as the actual experimental space. The virtual museum was 3D modeled based on its actual location, and the texture applied to the 3D model of the virtual museum was created by obtaining a basic texture through photography and then creating a physically based rendering (PBR) texture to make it realistic. The data thus created were matched with the same location and size of the real space so that users could feel the real wall when touching the virtual wall of the museum in

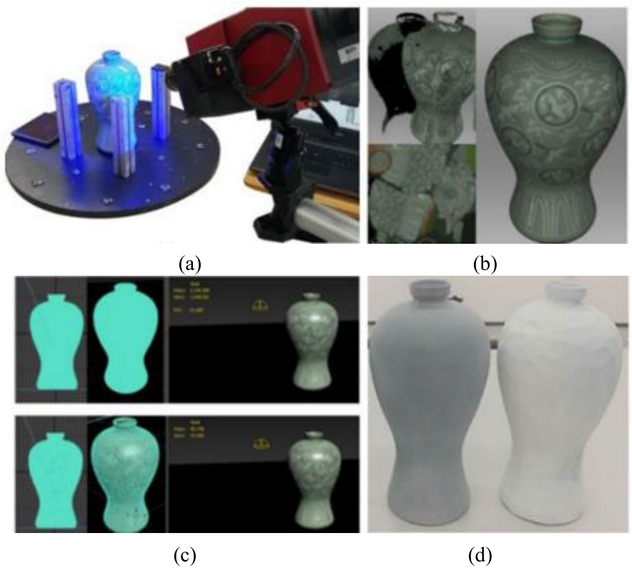


FIGURE 4. Process of creating a 3D asset of the ceramics artifacts: a) high-precision scanning, b) scanning data postprocessing, c) high-capacity scanning data retopology, d) 3D printing dummy creation.

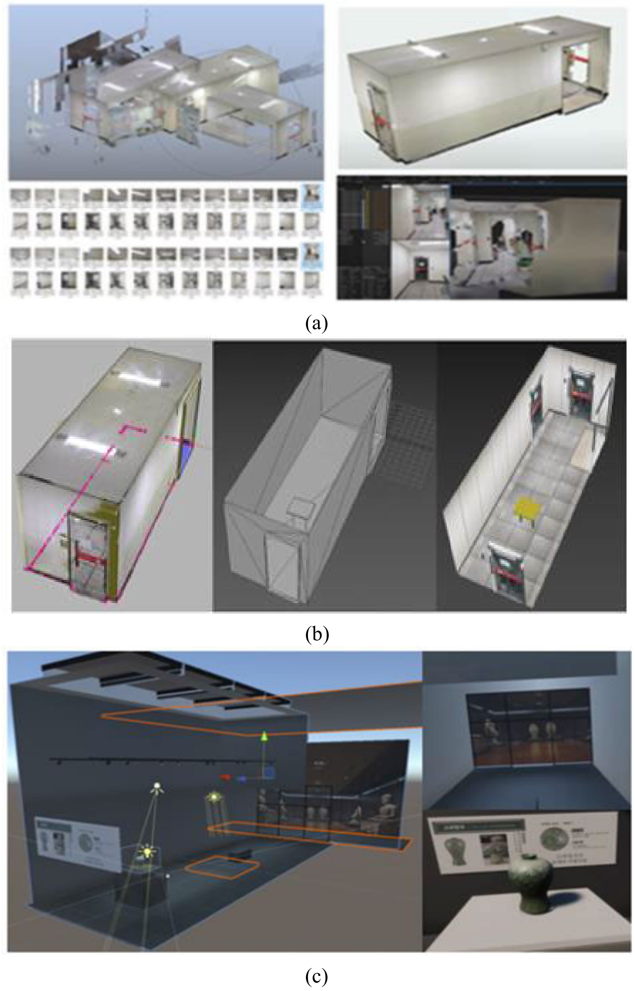


FIGURE 5. Process of creating a virtual museum 3D asset based on the physical space: a) 3D scanning and processing of real-world experimental environments, b) point cloud generation and 3D topology process, c) creation of 3D assets for the virtual museum based on real environment.

the virtual environment. The display case used in the interior environment of another virtual museum was also created as a 3D model by matching the shape and size of a real desk. Unlike artifacts, these display cases do not move during the virtual experience. Thus, no sensors were required, and the experiment was conducted by matching them to the same location in the virtual and physical spaces. Fig. 5 shows the process of creating a virtual museum with 3D data.

D. HMD-BASED MULTISENSORY VIRTUAL MUSEUM CONTENTS

The floor of the exhibit in the virtual museum content was made to resemble the kiln where the pottery were excavated. The environment was created through scanning, the actual spatial information was scaled with the VIVE Pro Eye HMD, and four sensors of the Base Station were used as the size controller; the basic settings of the virtual environment were set using Steam VR.

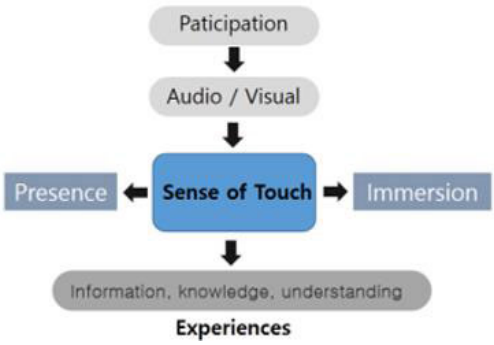
The 3D model data for the museum environment, including the 3D assets, the previously developed two-handed motion system, and the interlocking between virtual and dummy objects, were imported into Unity 3D in the FBX file format to implement the museum content environment. The Unity 3D version (2020.2.5f1) used integrates all the data; thus, that the museum's interior, created using scanned data, was expanded to generate a design configuration in the form of a viewing space for the ceramics special exhibition. To heighten the sense of immersion within the virtual museum, the floor of the exhibition room was modeled to resemble the kiln where the ceramics were excavated.

PBR textures, including base color, metallic, roughness, and normal bump map textures, were created and applied to achieve a realistic virtual museum environment.

When a user participates in the exhibition, the user wears the VIVE Pro HMD on the head and walks around the virtual space without a controller to enjoy the audiovisual experience, as in an offline museum exhibition. The users can also utilize the button in front of the ceramics to gain further information regarding the relic through photographs and videos. Further, users can view and touch the fixed artifacts with their bare hands. Users can also see and touch the immobilized artifacts with their bare hands, which gives them a sense of presence and a tactile experience. This increases immersion and creates a multisensory experience for the users, which helps them understand the information related to the artifacts (Fig. 6).

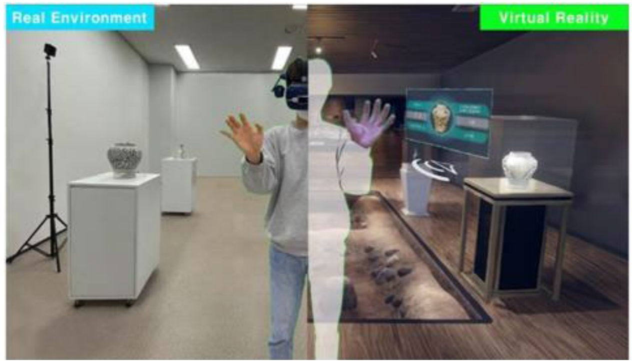
Through the interface information window, users can use their bare hands to rotate the artifact in the exhibition case while touching it. Finally, they can pick up the artifact with their hands and touch it with 6DoF. The HMD-based multisensory virtual museum content developed in this manner can be seen in Fig. 7. The multisensory virtual museum contents can deliver a strong sense of presence by enabling users to

(a)

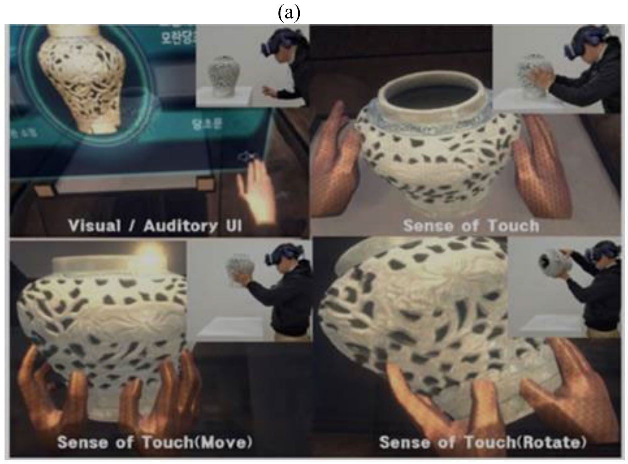


(b)

FIGURE 6. **HMD-based multisensory virtual museum environment: a) virtual depiction of the ceramics special exhibition, b) flowchart of the visit to the multisensory virtual museum exhibition.**



(a)



(b)

FIGURE 7. **HMD-based multisensory virtual museum contents: a) location matching between real and virtual spaces, b) user experiencing the multisensory museum exhibition.**

know, understand, and touch specific information when they participate in the exhibition.

Herein, the virtual museum content was implemented to visualize information regarding the artifacts and to realize immersiveness as a new experience by providing test, images, videos, and voices through the UI information window, with metadata information of the ceramic artifacts as audiovisual information. The aim of the multisensory virtual museum was to enhance the lack of presence through experiential viewing using the controller. In the conventional method, the museum VR exhibition content is presented with limited senses rather than as a special narrative approach. Our proposed method of viewing allows users to hold the ceramic artifacts on display in front of them and closely observe the detailed shapes and colors while also discovering new aspects of the artifact's aesthetics. Moreover, our method also allows users to touch non-display objects in the virtual museum, such as walls and tables, thus allowing them to experience a physically realistic spatial perception in the virtual environment.

IV. EXPERIMENTS

This section describes the experimental methods and procedures for comparing the proposed HMD-based multisensory virtual museum contents with conventional virtual museum contents that provided audiovisual interaction to users. It also describes the analysis of the questionnaire responses provided by participants to evaluate the usability of the two methods. Further, it discusses the effects of the two methods on the sense of presence and immersion. Herein, the differences between the methods applied to the VR environment were assumed to have a significant influence on the users' preference for the VR content.

Our research questions were as follows.

RQ 1. In HMD-based virtual museum environments, is tactile interaction with bare hands with multisensory museum content more impactful than traditional methods for increasing the sense of presence when viewing the artifacts?

RQ 2. When viewing the artifacts in the virtual museum, did the multisensory experience help you immerse yourself in the content?

RQ 3. While viewing the artifacts in a virtual museum environment, how would you like to interact and prefer to view them?

In addition, HMD-based multisensory virtual museum contents are realistic VR contents. The participants of the experiment experienced two methods of viewing artifacts in a virtual environment, and their sense of presence, immersion, and satisfaction were analyzed through usability evaluation based on their responses to a questionnaire.

TABLE 2. Participants in an HMD-Based virtual museum experiment.

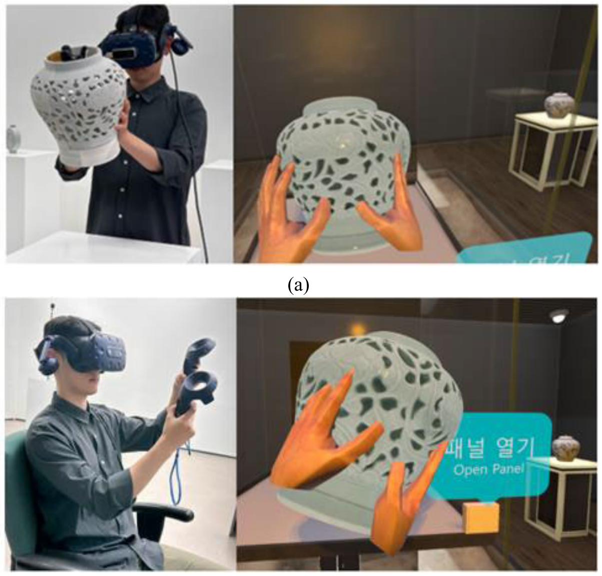
Classification		Results
Sex	Male	11 persons
	Female	21 persons
Age	20s	23 persons
	30s	8 persons
	60s	1 person
VR experience	Yes	25 persons
	No	7 persons

A. PROCEDURE

All investigations reported in this paper were conducted as a graduate research project. For the usability evaluation, 32 participants were recruited using a school bulletin board. All participants reported at the experimental site at a predetermined time. Before starting the experiment, the purpose, procedure, and caveats of the experiment were explained. In the experiment, each user experienced the virtual museum in two different ways and completed a survey about each method. After receiving written consent and an explanation of the experiment, the participants viewed the HMD-based multisensory virtual museum contents and the conventional virtual museum contents. Of the 32 participants in the experiment, 16 were asked to use the multisensory method first and then the conventional method, whereas the remaining 16 were asked to use the methods in the reverse order TABLE 2. After completing all the procedures, the participants were asked to respond to a questionnaire, and they were given 20 min to fill out the evaluation forms for both methods. In return, a small honorarium was paid to the participants. The results of the survey were analyzed using an independent samples t-test to determine the difference in experience between the two methods. Additionally, differences between the groups with and without prior experience with VR, augmented reality, and mixed reality were elucidated.

B. EXPERIMENT

The purpose of the experiment was to compare the interactive user experience of the existing HMD-based virtual museum content and the proposed seeing, hearing, and touching multisensory VR content. The experimental conditions, including the VR museum, and horizontal and vertical laboratory space were the same. The existing virtual museum is displayed by an HMD and interacted with using a controller, whereas the proposed virtual museum is interacted with using bare hands and by walking through it. The experimental results can be used to provide a more enhanced user experience in terms of presence and immersion, and identify the preferences of visitors according to their satisfaction with the contents. The artifacts exhibited in the virtual museum were all ceramic materials. In the first method for multisensory museum contents, visitors could walk around the museum and interact with the exhibited ceramics with their bare hands to gain a sense of touch (Fig. 8).



(a) (b)

FIGURE 8. Comparison between usability tests conducted with two viewing methods: a) conventional virtual museum, b) multisensory virtual museum.

Pottery information was provided as a UI, and visitors could access the text and voice information while viewing the artifacts. The second type of virtual museum exhibition used a controller to interact with the artifacts, with limited movement and directional controls to move through the space by pressing the arrows on the controller. The interior of the museum in each experimental virtual environment was the same and displayed a special ceramic exhibit. With both methods, visitors required approximately 10 min to visit the virtual museum. The visitors could interact with the ceramic artifacts exhibited in the virtual museum in a multisensory manner, wherein the artifacts could be held, moved, and rotated under the same conditions. Therefore, the participants could experience the multisensory virtual museum using bare hands in the proposed method and the virtual museum using the conventional audiovisual controller (Fig. 8).

V. RESULTS

We conducted an experiment to compare the usability of the virtual museum content through two methods and obtained the results from 32 participants. In this section, we report the results of spatial presence, content immersion, and VR content preference in relation to users' sense of touch. Table 3 lists the questionnaire that the participants answered after experiencing the two methods. Before analyzing the results, we conducted a reliability analysis of the items in the questionnaire to determine their internal consistency reliability. The reliability coefficients (Cronbach's alpha) for presence, immersion, and preference were 0.700, 0.854, and 0.861, respectively, thus indicating relatively high reliability. Subsequently, we then conducted an independent sample t-test, which is often used to compare the means of two different groups, to check the difference in the presence, immersion, and preference scores between the two methods.

TABLE 3. Experiment evaluation questionnaire.

Variables			Multisensory virtual museum / Conventional virtual museum	Reliability	
				CICT	Cronbach's alpha
Presence	Cognitive involvement	Peripheral involvement	I was aware of my surroundings and objects	0.438	0.667
		Sensory relevance	Sensory elements such as sight, sound, and touch made the exhibition feel realistic.	0.519	0.629
	Interactivity	Matching clarity	The physical and virtual representations were well matched.	0.572	0.580
		Realism of representation	The components of the exhibit are realistically represented.	0.450	0.660
Immersion	Antecedents	Clear goals	I have clearer information to view and understand pottery.	0.481	0.849
		Instant feedback	Instant feedback on my actions was provided.	0.708	0.825
		Challenge and ability balance	The viewing was organized at just the right level of difficulty, neither too easy nor too hard.	0.648	0.837
	Course elements	Behavioral awareness unity	The viewing was spontaneous and automatic, without conscious effort.	0.652	0.833
		Stay on task	I completely focused on the show.	0.661	0.832
		Sense of control	It made me feel like I was in control of the situation.	0.617	0.835
		Loss of self-consciousness	While viewing the exhibit, I lost awareness of my surroundings and became immersed in the activity.	0.491	0.848
	Result element	Distorted sense of time	Time seemed to pass unusually quickly or slowly.	0.446	0.859
		Self-satisfying experience	The viewing experience was satisfying.	0.661	0.832
Preference	Experience satisfaction	Intent to reuse	I would use this method for my next visit to the museum.	0.756	·
		Willingness to recommend to others	I will recommend the VR viewing technology to others.	0.756	·

TABLE 4. Sense of presence according to viewing method.

(*N*=64)

Classification		Service Satisfaction Score			$t(p)$
		N	Mean	Standard Deviation	
Presence	Conventional Virtual Museum	32	3.734	0.595	-5.104(0.001)***
	Multisensory Virtual Museum	32	4.453	0.529	

*p<.05, **p<.01, ***p<.001

The sense of presence involves cognitive involvement and interactivity and is further composed of peripheral involvement, sensory involvement, clarity of matching, and realism of expression. It is an evaluation measure that examines the realism indicator by checking the difference in the perception of the museum environment and artifacts when the user experiences the two viewing methods through the experiments. Additionally, it examines if the viewing of artifacts seems realistic and whether the artifacts in the exhibition are realistically represented. The mean (standard deviation) of the sense of presence was 3.743 (0.595) for the conventional virtual museum contents and 4.453 (0.529) for the multisensory virtual museum contents (Table 4). Consequently, we obtained $t = -5.104$, $p = 0.000$, which is statistically significant based on the significance level of 0.001. Therefore, the null hypothesis cannot be rejected because the means of the two methods differ. Hence, the opposite hypothesis was adopted, thus indicating a difference in the sense of presence depending on the viewing method. The sense of presence felt when experiencing the multisensory virtual museum contents was superior, as confirmed by a relatively higher mean score than that of the conventional virtual museum content method.

The items related to immersion comprise antecedents, processes, and outcomes. In detail, it consists of clear goals, immediate feedback, perceived ability to challenge, sense of unity, focus on the task, sense of control, loss of self-consciousness, distortion of time, and self-satisfying experience. In the experiment, when experiencing two things, a virtual museum that includes tactile sensations and existing museum contents, the ease of interaction with relics and pottery, the difficulty of accurate feedback and viewing methods, the degree of concentration through natural exhibition viewing, and the concentration during viewing, which corresponds to the participant not feeling the sense of time. The concentration during viewing can reveal the sense of immersion as satisfaction with the content. Depending on the viewing method, the mean (standard deviation) for immersion was 3.828 (0.789) for the conventional virtual museum contents and 4.343 (0.615) for the multisensory virtual museum contents (Table 5). The result of the independent sample t-test was $t = -2.916$, $p = 0.005$. Thus, the alternative hypothesis was adopted, thereby confirming a difference in immersion depending on the viewing method. Therefore, the multisensory virtual museum contents showed a relatively higher mean score for immersion than the conventional virtual museum content method.

Finally, the evaluation items for preference for the two methods consisted of satisfaction and intention to recommend as independent variables of the experience factor. When experiencing the VR contents, users can confirm their intention to

TABLE 5. Average difference in immersion score by viewing method.

(*N*=64)

Classification		Service Satisfaction Score			*t*(*p*)
		N	Mean	Standard Deviation	
Immersion	Conventional Virtual Museum	32	3.828	0.789	-2.916(0.005)**
	Multisensory Virtual Museum	32	4.343	0.615	

*p<.05, **p<.01, ***p<.001

TABLE 6. Average difference in preference score by viewing method.

(*N*=64)

Classification		Service Satisfaction Score			*t*(*p*)
		N	Mean	Standard Deviation	
Preference	Conventional Virtual Museum	32	4.516	0.724	-2.226(0.031)*
	Multisensory Virtual Museum	32	4.828	0.327	

*p<.05, **p<.01, ***p<.001

recommend the viewing experience to other users based on their satisfaction with the choice of viewing method and the related experience. After experiencing both types of virtual museum content, the users could comment on what other artifacts they would like to experience in the future and how they would recommend them to others. The mean (standard deviation) for preference was 4.516 (0.724) for the conventional virtual museum contents and 4.828 (0.327) for the multisensory virtual museum contents (Table 6). The t-test was conducted in the same manner, and the result was $t = -2.226$, $p = 0.031$, which is statistically significant based on the significance level of 0.05. Therefore, as the means were different, the null hypothesis could not be rejected and the opposite hypothesis was adopted, thus indicating a difference in preference according to the viewing method. Evidently, the multisensory virtual museum contents exhibited a relatively higher average score compared with the conventional virtual museum contents and is better preferred by the users. In the study to investigate the differences in presence, immersion, and preference depending on the viewing method according to prior experience with VR, augmented reality, and mixed reality, the number of participants with prior experience was 25, and the number of participants without prior experience was 7. Before analyzing the differences between the two groups, a normality test was performed, and the non-parametric Mann–Whitney U test was used instead of the parametric t-test, but the differences between the groups were not significant. This result is likely due to the unbalanced ratio of participants between the two groups and the insufficient number of total participants. Additional data are needed to confirm the results of this experiment.

In addition to the quantitative evaluation, the qualitative evaluation by the participants revealed that both virtual museum experiences made them feel like they were in a real museum owing to the visually realistic graphics. A common comment was regarding the sense of touch experience. P4 said, "It was nice that the glass cases of the museum exhibits disappeared, and you could hold the pottery in your hands, rotate it, and examine it closely." P21 said, "It was good to walk around the virtual museum and touch the walls of the museum and the surfaces of the furniture displayed, and to pick up the artifacts with my own hands to understand the information on the ceramics." P23 said, "The sense of touch in the virtual museum gave me a new experience and allowed me to focus on learning the information on traditional ceramics." P32, a full-time professor at the school, commented, "A virtual museum with this kind of sense of touch would be a great content if it could be used as a teaching material for elementary, middle, and high schools." In the qualitative evaluation, participants reported a positive viewing experience when viewing the virtual artifacts with tactile interaction, compared to viewing them without tactile interaction, including "interesting," "more alive," "informative," "like touching the real thing," "more realistic," "new," "more immersive," and "fun." Some participants said, "I could actually see my hand, which made it come alive," indicating a positive impact. One participant said, "It was lively because I could actually see my hand," implying that being able to see their hand movements had a positive impact. In addition, one participant said, "The experience of actually touching cultural objects is new because it can only be done in virtual reality," demonstrating that they felt a new viewing experience that cannot be delivered in a real museum and that the intention of this paper was properly conveyed. In addition, there were positive responses to the ease of operation compared to the tactile experience, such as "I can hold the artifact in my hand and observe various aspects," "I am satisfied with the way I can turn and touch the artifact," and "It was good to move it at my will." As a result, the proposed method shows more positive results in tactility, visualization of the user's hand, the realization of experiences not possible in the real world, and ease of operation.

VI. DISCUSSION

We conducted a comparison experiment between the virtual museum contents reflecting existing VR technology and the multisensory virtual museum contents applying the proposed tactile technology (Fig. 9). The sense of presence and immersion in the VR contents significantly improved with the introduction of the sense of touch for the objects in the virtual environment. This indicates that applying a technology that matches the visual perception of virtual objects with the tactile perception experienced when holding and touching real objects with bare hands is effective in improving the level of experience in the virtual environment. Additionally, interaction using both hands helped enhance the experience level compared with the existing controller-based interaction by enabling intuitive manipulation of the virtual objects in terms of functionality. It is interpreted that the preference for the viewing method using the sense of touch was higher than that for the existing method because it was satisfactory in terms of sense of presence and immersion.

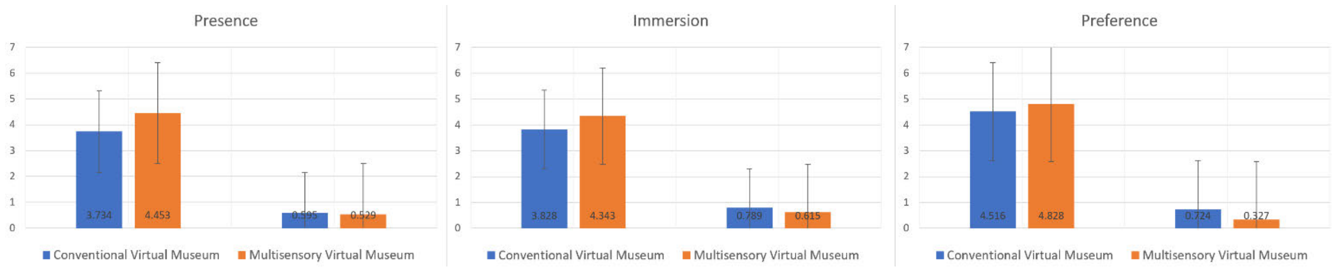


FIGURE 9. Experiment ratings for two different viewing methods.

A. ANALYSIS OF FINDINGS

According to the results of the two methods, multisensory VR contents were more positively evaluated than the traditional audiovisual and controller-based viewing methods in terms of presence, immersion, and preference. The provision of the sense of touch in addition to the sense of sight and hearing enhanced the spatial presence of the artifacts in the virtual museum environment than the traditional method, thus suggesting that multisensory content should be provided. Steuer et al. reported that spatial presence is a crucial factor in a virtual environment [49]. Slater et al. [50] and Slater and Usoh [51] described the sense of presence as a state of being in a virtual environment where the user is aware that they are in a virtual environment but can be misled by the interaction or feel that they are in a virtual world.

The experimental results of this study suggest that the impact of tactile interaction using bare hands in multisensory-based museum contents to enhance the sense of reality when viewing artifacts in an HMD-based VR museum environment is higher than that of conventional audiovisual contents. Additionally, the implementation of interactions to recognize an artifact by visualizing the user's hand and naturally touching the pile renders the exhibition viewing in the virtual environment more realistic, and results in high cognitive and sensory engagement. Thus, the participants gained a new experience beyond the existing museum content. We further confirmed that the participants felt a richer sensory experience when receiving audiovisual information regarding the artifacts through the UI based on text and voice description and additional tactile information by directly touching the artifacts.

The traditional controller-based VR content also allows the users to hold and rotate virtual objects as in the proposed method, but the evaluation of reality seems to be low, as it is not as intuitive as touching the relics with bare hands and the users cannot feel the touch and weight.

In the case of immersion, research has shown that the cognitive scale that allows users to feel as if they are in reality without a sense of heterogeneity must be increased in a virtual environment. Additionally, according to Csikszentmihalyi's flow theory, clear goals and immediate interactions are important factors in improving the quality of experiences [52]. As a result of increasing content immersion by providing multiple senses compared with the existing method when viewing the artifacts of the virtual museum presented in the experiment of this study, it is easy to adapt to the immediate feedback and viewing difficulty suitability according to the user's natural interaction in the above elements, and to feel immersive. In terms of the content use process, we confirmed that visitors in the multisensory virtual museum content were able to appreciate and concentrate on the artifacts through natural interaction without conscious effort. Additionally, we found that the sense of control in these was stronger than that in the existing virtual museum content when manipulating virtual dummy artifacts. This implies that it was possible to confirm that it exists as controlled by the user. Consequently, the participants felt integrated with the virtual world rather than identifying themselves as distinct people, experienced a faster passage of time, and felt great satisfaction. Furthermore, the visualization method was more diverse compared with existing virtual museums. The sensory museum came out relatively high. This suggests that adding sensory elements such as the tactile sensation of natural interaction in VR can increase immersion and overcome the limitation of not touching artifacts in real museums. Evidently, it created a high sense of immersion.

As for the last question, when viewing artifacts in a virtual museum environment, the multisensory virtual museum was rated higher compared with the existing virtual museum.

According to the user's experiment results, the proportion of participants who answered that they would like to use the proposed relic appreciation method in the future, along with the possibility of recommending it to others, was higher compared with those who preferred using the existing method. A positive evaluation seems to be related to the new experience of touching the artifacts. This suggests that enhancing presence and immersion is important for increasing the preference for VR content, as the VR content aims to be a realistic sensory experience. Recently, museums have been continuously expanding their VR content, as it can effectively convey information and attract visitors by providing realistic experiences, and the results of this study suggest that the proposed method is effective in increasing the attractiveness of the content.

B. LIMITATIONS AND FUTURE WORK

A limitation of this study is that the user's hands can be visualized in the virtual environment only when they are within the range of the Leap Motion sensor. If the user's hands are obscured while touching the 3D printed dummy, the Leap Motion sensor will not recognize the hands and the virtual hands will be lost in the virtual environment. VR gloves robustly tracks the hand regardless of its position; however, this may cause hindrance to the tactile experience while wearing them. Another limitation is that the VIVE Pro HMDs used in this study require a separate PC and cable connection to operate. This can make it difficult for the participants to move freely around the exhibit. Recently, HMDs that can be operated without a PC connection, such as Meta Quest, VIVE Focus, and VIVE XR Elite, have been released and may exhibit better performance than their PC-connected counterparts in the future. These devices can be utilized to overcome the limitations of mobility constraints.

In future research, we aim to build a virtual museum that can provide visitors with a realistic viewing experience incorporating the sense of touch without having to visit the museum in person. The proposed system can be applied to various museums with remote accessibility, such as overseas museums. Additionally, we plan to study ways to recognize detailed differences in the texture, size, and weight of artifacts in a virtual environment to realize a more realistic sense of tactile feedback. By doing so, we hope to enhance the user experience and improve the effectiveness of the system.

VII. CONCLUSION

This study addressed the limitation of virtual museum experiences, which predominantly focus on audiovisual senses, by proposing VR contents that facilitate multisensory experiences. The proposed method uses 3D printing technology to materialize virtual pottery, thereby enabling users to engage with the artifacts with the sense of touch. User evaluation results demonstrated an enhanced sense of presence and immersion, thus leading to a greater preference for the content. These results underscore the necessity of actively incorporating multisensory experiences when creating virtual contents. VR technology can effectively provide a more immersive and impactful experience by enabling multisensory engagement. Therefore, regardless of other disabilities, touching what you see can provide a three-dimensional understanding of the nature of cultural objects. Consequently, extensive research is required to explore and integrate multisensory experiences in cultural content creation, particularly in the context of virtual museums. Future research directions should focus on effectively integrating multisensory experiences into various cultural heritage fields and developing appropriate technologies to support such experiences. In addition, research should investigate user experiences through UIs to effectively deliver multisensory experiences, incorporating the latest equipment and technologies. Furthermore, virtual museum content that incorporates multisensory-based VR has the potential to cultivate users' curiosity about different historical sites spanning various periods and geographic locations. Therefore, research on how to effectively utilize this technology not only in the cultural industry but also in educational settings is crucial. Continuous research endeavors in this field are anticipated to further advance VR technology and broaden its applications within the cultural industry and the educational sector.

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