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ResponsiveView: Enhancing 3D Artifact Viewing Experience in VR Museums

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Fig. 1: Demonstration of ResponsiveView with controller-based inputs. (a) Model-predicted pedestal height and the best viewing distance. Users can point and select to teleport. (b) A front view captured from the best viewing point. (c) Grab an artifact in its predicted size for handheld interactions (c1) scaled down from its actual size (c2).

Abstract—The viewing experience of 3D artifacts in Virtual Reality (VR) museums is constrained and affected by various factors, such as pedestal height, viewing distance, and object scale. User experiences regarding these factors can vary subjectively, making it difficult to identify a universal optimal solution. In this paper, we collect empirical data on user-determined parameters for the optimal viewing experience in VR museums. By modeling users' viewing behaviors in VR museums, we derive predictive functions that configure the pedestal height, calculate the optimal viewing distance, and adjust the appropriate handheld scale for the optimal viewing experience. This led to our novel 3D responsive design, ResponsiveView. Similar to the responsive web design that automatically adjusts for different screen sizes, ResponsiveView automatically adjusts the parameters in the VR environment to facilitate users' viewing experience. The design has been validated with two popular inputs available in current commercial VR devices: controller-based interactions and hand tracking, demonstrating enhanced viewing experience in VR museums.

Index Terms—Virtual Reality, Responsive Design, Virtual Museum

1 Introduction

People receive an abundance of visual information whenever their eyes are open, but not all of this input may be relevant to their behavioral goals. In the context of museums, professionals implement object placement strategies to enhance visitors' ability to view collection items effectively. Artifacts are arranged within the visitors' line of sight to maximize visual engagement. For particularly significant objects or those with intricate details, additional aids such as multimedia interactive devices may be provided. With the rise of Virtual Reality (VR) technology and the increasing availability of commercial VR Head-Mounted Displays (HMDs), VR museums have emerged as a novel platform for cultural engagement. However, VR museums possess distinct characteristics that set them apart from traditional museums. Currently, there is a lack of research on developing relevant guidelines to enhance visitors' viewing experiences in VR museums.

Our study aims to improve visitors viewing experience in VR museums. We draw inspirations from responsive web design alongside previous works in traditional museums, VR museums, and 3D interactions. We identify an opportunity to improve the viewing experience by integrating appropriate artifact displays and scalable sizes, with teleportation and scaling manipulation based on users' eye level, artifact's initial size, and the richness of their details. Specifically, we conducted a study to understand the optimal display for fixed-position viewing of 3D artifacts in a VR museum (**RQ1**) and the optimal size for handheld interaction (**RQ2**). We recorded the viewing preferences of twenty users with twenty museum artifacts, presenting three predictive formulas that determine the pedestal height (`F1`), the optimal viewing distance (`F2`), and the optimal size for handheld interaction (`F3`).

Based on results of the first study, we developed ResponsiveView (see Fig. 1), a responsive method designed to dynamically enhance the viewing experience in VR museums. When users enter the VR museum, our system automatically retrieves the environment and user data to 1) change the pedestal height for each artifact, 2) facilitate automatic teleportation to the optimized viewpoint, and 3) adapt the artifact to an appropriate size for interactions. We implemented these features across two different 3D interaction techniques: controller-based and hand tracking.

To evaluate whether ResponsiveView can improve visitors' viewing experience in VR museums (**RQ3**), we conducted Study 2 with 24 participants, comparing the non-responsive and responsive conditions using two different techniques. With *controller-based input*, ResponsiveView resulted in improved locomotion efficiency, usability and user experience, user satisfaction, and the sense of performance in VR

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museum visiting. With *hand tracking input*, ResponsiveView demonstrated enhanced locomotion efficiency, user engagement, satisfaction, and reduced frustration.

Our work advances interaction design in VR and has significant implications for the fields of digital and virtual heritage. Specifically,

- We make public a data set ($n = 400$), showing user-elicited viewing preferences for museum 3D artifacts in VR museums.
- We developed three predictive formulas to set optimal pedestal height, viewing distance, and handheld size based on users' eye level, artifact dimensions, and their level of detail.
- We introduce ResponsiveView, a novel 3D responsive method for virtual environments.
- We validated ResponsiveView with two popular input techniques: controllers-based and hand tracking, with results showing that ResponsiveView improves users' 3D artifact viewing experience in VR museums.
- We provide design guidelines for researchers and practitioners to explore more effective solutions to viewing and interacting with 3D objects in VR.

2 Background

2.1 Responsive Design

Responsive design is an approach that is commonly adopted in web design. It allows 2D user interface to adjust automatically to the device's layout, enhancing usability, navigation, and information retrieval [3,17,42]. Responsive Web facilitates designers create a visually appealing experience that works well independent of the browser size and constraints of accessing devices. From a user experience perspective, responsive design on mobile devices leads to websites that demand fewer user interactions, such as scrolling and clicking, and reduces the total number of errors in comparison to non-responsive ones.

In this work, we draw inspiration from the concept of responsive design and apply it to Virtual Reality (VR), aiming to enhance users' viewing experience in VR museums. In this section, we ground our work in (1) how people view artifacts in physical museums, and study (2) how to map the viewing behaviors in VR museums.

2.2 Viewing Artifacts in Physical Museums

Collections in physical museums are displayed in fixed locations, with exhibits safeguarded by display cases or regulated viewing distances [10]. In this context, museum professionals strategically arrange the exhibits to align with the human visual range, ensuring optimal visibility. Tools and systems such as magnifying glasses and interactive multimedia systems are sometimes provided to enhance the viewing experience.

The practices of artifact display are predominantly featured in various museum or Interior space design guidelines [10,28,41]. Generally, visitors' gaze and attention are directed towards objects of interest, prompting them to approach the exhibit at a fixed location for a closer examination [2]. Notably, the *height* at which artifacts are displayed is crucial for ensuring they remain within the visitor's visual range. For example, the Glasgow Museum Display Guidelines [10] suggest six different height ranges for exhibit placement, attuned to the general visitors' viewing height. These display height classifications take into account different factors, such as the size of the artifacts (General, Small, Very small), the depth of the display, whether they are suspended from the ceiling, and if they are within a reachable, protected area. Additionally, the *viewing distance* is another vital factor that determines the artifact's placement and the space available for visitor movement [28]. Previous work showed that the ideal viewing distance of museum artifacts can range from 91.4 cm to 147.3 cm [28] or 105 cm based on average adult eye level, 155 cm [41]. However, many artifacts in museums are complex in shape and rich in visual details. Adhering to these suggested ranges may not be sufficient for visitors to fully observe the visual information contained within them, especially for small and intricately detailed objects.

Museums have employed various tangible and digital methods to augment visitors' ability to appreciate intricate and delicate artifacts, calligraphy, and paintings that are rich in detail. Example methods include providing magnifying glasses, designing specialized display cabinets with movable magnifiers, and implementing interactive systems. The rationale for providing a magnifying glass is straightforward - it enables users to enlarge specific details, allowing a closer examination of intricate features that might otherwise be difficult to see at the object's standard size. Additionally, some screen-based interactive systems go beyond simple zooming capabilities. For example, the *Australian Museum for Applied Arts and Sciences* adopted an icons 3D touchscreen to enable users to drag or rotate the view [25], revealing hidden aspects of 3D objects, such as the bottom, back, top, or interior, which may be obscured by the object's physical placement.

3 Related Work

Although curators and developers can replicate all aspects of real museums in VR, protective settings are no longer necessary. Visitors can interact with exhibits in a more flexible manner with augmented capabilities [32]. To map the user's viewing behaviors in the physical museums to VR museums, we primarily focus on two aspects: *movement* and *manipulation*. As previously discussed, typical behaviors in physical museums include walking toward an artifact of interest and viewing it at an appropriate distance, often beyond a protective zone or a glass case. However, applying the same strategies used in physical museums to VR environments may not yield the same quality of user experience. A notable enhancement in VR museums is the ability of visitors to hold artifacts in hand, enabling 3D manipulations with them as if they are manipulating them like any other physical object. We explore these two typical behaviors in the following subsections.

3.1 Movements in VR museums

One significant challenge in VR museums is the simulation of walking - it is hard for users to feel the sense of wandering around the museum and walking towards an object of interest. Realistic walking in VR demands tracking users' movement within a large physical space, which may not always be practical or feasible [4]. In response, researchers have proposed alternative continuous locomotion techniques incorporating walking-based methods [16,24,31]. Nonetheless, these approaches come with their own limitations and complexities, such as being unnatural for a museum context [38] and requiring additional devices and substantial setup efforts [18]. Additionally, continuous locomotion techniques can increase the risk of motion sickness [22,36,43], which can often be severe for many users. Given these limitations, nearly all commercial VR museum applications have opted for a discrete locomotion technique: *point and teleport* [5].

In the studies of the *point and teleport* technique, researchers have measured variables such as the user's offset value to the target point and the number of teleportation required to reach it [5,18,40]. In a VR museum utilizing this technique, users need to constantly adjust their position to reach a comfortable viewpoint in front of the artifact. Various commercial VR museum applications have made efforts to minimize user effort and facilitate viewing experiences. For example, *the Kremer Collection VR Museum*[1] allows users to point at a painting to teleport directly to a preset distance in front of it, reducing the need for multiple teleport and orientation adjustments. However, this application adopts a constant viewing distance for all paintings without considering their dimensions. This violates the museum exhibition guidelines that recommend different viewing distances based on the varying sizes of objects [10]. Conversely, *Virtual Museum De Fornaris*[2] has teleportation points strategically positioned to fit the paintings within the field of view of the HMDs, with a consideration of the paintings' varying sizes. However, when it comes to observing *3D artifacts*, VR museum applications lack similar design considerations for auxiliary views. Shuai et al. [30] explored a related topic and

[1] `https://store.steampowered.com/app/774231/The_Kremer_Collection_VR_Museum/`

[2] `https://www.meta.com/experiences/pcvr/3926465470728547/`

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investigated the effects of object complexity (occlusion, structure, and texture) on 3D object observation in VR. However, their study had limitations, as it focused on abstract geometries rather than actual virtual museum artifacts, leading to a lack of comprehensive evaluation.

3.2 Manipulations in VR museums

Manipulations contribute significantly to the museum viewing experience. The use of magnifying glasses and interactive systems in physical museums serve two primary purposes. Firstly, they function to enlarge items or intricate details thereof, and secondly, they facilitate the rotation of 3D objects to view obscured sections, such as the bottom, back, top, or interior.

In VR museums, although it is possible to emulate the solutions by offering magnifying glasses or interactive panels, these adaptations essentially translate to two fundamental 3D interaction tasks: *rotation* and *scaling* [4]. One natural manipulation technique for rotation is 6-DoF hand [20], which allows users to hold objects and rotate them by naturally twisting their wrists and arms. On the other hand, scaling, despite lacking a direct real-world equivalent, is a fundamental manipulation task employed in 3D user interfaces [4]. Take 6-DoF hand [20] as an example, while holding an object with one hand, users can reach out with the other hand to grab a point in space beyond the bounding box and adjust the distance between their hands to modify the object's scale. However, due to the absence of such operations in the real world, there are few guidelines addressing this practical need. Additionally, relevant research in the VR domain remains limited.

Based on the above review, we identify two research gaps: (1) there is no specific guideline for fixed-position artifact displays in VR museums, and (2) it is unclear how hand-based interactions should be designed for artifact viewing in VR museums.

4 Study Design

To address the gaps in the related work, we propose two studies. The first study focuses on identifying optimal viewing parameters. We aim to apply the results and findings of the first study to guide the design and implementation of the ResponsiveView system. The responsive system is then evaluated in the second study to assess its efficiency in the viewing experience of 3D artifacts in VR museums. Specifically, the two studies aim to address the following research questions (RQs):

RQ1 *How to determine the optimal pedestal height and viewing distance for 3D artifacts viewing in VR museums?*

RQ2 *How to determine the optimal size for handheld interaction with 3D artifacts in VR museums?*

RQ3 *Does ResponsiveView enhance the viewing experience of 3D artifacts in VR museums?*

The research is approved by the University Ethics Committee of Xi'an Jiaotong-Liverpool University (ER-SAT-11000011420220928203255).

5 Study 1: Determining Factors of Optimal Viewing

The first study aims to investigate optimal pedestal height and viewing distance for fixed-position artifacts viewing (**RQ1**) and optimal size for handheld interaction with 3D artifact (**RQ2**) in VR museums.

Previous work showed that apart from the *size* of the artifact, its *detail richness* is also essential in its display [10]. In addition, a person's eye level is always included when determining artifact display [10, 28]. Therefore, we studied their impact on determining the optimal pedestal height, viewing distance, and handheld size for interaction.

5.1 Apparatus and Implementation

We used a computer equipped with an Intel Core i7-12700k CPU running at 3.60GHz, 32GB of RAM, and a NVIDIA GeForce GTX 3080 graphics card with 16GB of RAM. A Meta Quest Pro headset with two handheld controllers was used, featuring a resolution of 1800×1920 per eye, a 90 Hz refresh rate, a horizontal field of view of 106 degrees and a diagonal field of view of 96 degrees.

The system was built using Unity (version 2022.3.17f1) under the 3D Universal Render Pipeline. We incorporated the Meta XR Core package (version 2.2.3), XR Interaction Toolkit (version 2.5.2), and the XR Plugin Management (Version 4.4.1). For locomotion, we implemented both steering (with a moving speed of 1.4 m/s [21] and a turning speed of 60 degrees/s [1]) and teleportation (liner-instant, with a maximum distance of 18 m [19]), allowing users to switch between them at will. In addition, we used intuitive direct interactions for rotating and scaling, which replicate natural interactions with physical objects for manipulations [20, 34].

We sourced 20 artifacts with Creative Commons domain license from *Sketchfab*[3]. To ensure environmental realism and system replicability, we used the *Art Gallery Museum VR*[4] produced by a professional art studio to construct the VR museum. To minimize the lighting and environment effect, our lighting rendering adhered the specification of this package, using spotlights based on standard lighting settings for each artifact (see Fig. 2).

5.2 Procedure and Tasks

The experiment consisted of three parts totaling around 40 minutes.

Consent and demographics information. Participants were first informed of the purpose of the study and signed a consent form before completing a demographic questionnaire regarding their gender, age, vision status (normal or corrected), and experience with VR and museum visits.

Tutorial. To mitigate the influence of unfamiliarity with VR, we prepared a tutorial providing (1) instructions on how to steer, teleport, switch between locomotion methods, and mark preferred viewpoints, and (2) guidance on selecting, grabbing, rotating, and scaling handheld objects, as well as marking the status of preferred objects. Each experimental session started with the tutorial scene.

Tasks with artifacts. Participants were positioned in a VR museum with a fixed position and direction towards the artifact. They could only move forward and backward along the Z-axis and view the artifacts sequentially without moving from their positions. Participants were asked to complete three tasks:

(1) Set pedestal height: use the `A` and `B` buttons on the right controller to raise or lower the pedestal for an optimal view.

(2) Set distance to artifact: use the left controller's joystick to steer forward or backward for the best viewing distance.

(3) Resize the artifact: press the `grip` buttons on both controllers and change the distance to scale the artifact for an ideal view.

5.3 Data Collection

Image Processing. To quantify artifacts' detail richness, we captured their front-facing images, ensuring consistent height in the picture. We then used Adobe Photoshop (Version 25.7) to cut out the image and remove the background (see Fig. 2). Wang et al. [37] showed that low-level features such as the number of edges and image contrast can be retrieved by image processing. We used Matlab (Version R2020a) to process the image and obtained quantified measures. Specifically, we applied the Sobel operator to calculate the Sobel edge counts (E), which quantifies the number of edges detected in an image and highlights areas of high spatial frequency. Brightness gradient standard deviation (B) measures the variation in brightness levels across the image. A higher standard deviation indicates a greater range of brightness, suggesting more contrast and detail. Similarly, the gray gradient standard deviation (G) assesses the variation in gray levels in the image. It reflects how much the gray values change, which can indicate texture and detail richness in the image. The results are shown in Table 1.

Logged Data. Our system logged the following data:

(1) user-defined pedestal height (H_p), measured from the top of the pedestal to the ground along the Y axis;

[3] https://sketchfab.com/

[4] https://assetstore.unity.com/packages/3d/environments/art-gallery-museum-vr-230478

Fig. 2: Images of twenty artifacts rendered in Unity under an overhead spotlight at a 30° angle.

Table 1: Descriptive table showing 20 artifacts with their size and detail richness (sorted by artifact height).

	Size			**Richness in Details**		
	Height (H, cm)	**Width** (W, cm)	**Depth** (D, cm)	**Edge Counts** (E, k)	**Brightness Contrast** (B)	**Gray Contrast** (G)
A1 Miniature Garden Seat	4.40	3.80	3.80	109.86	69.67	3.23
A2 Cut Down Porcelain Vase	11.00	11.00	11.00	36.15	64.02	2.17
A3 Potala Guanyin	15.10	9.90	7.50	73.50	38.08	3.70
A4 Vase	15.40	10.40	10.40	77.73	86.69	3.43
A5 Raft Cup	16.00	15.00	17.00	238.34	96.95	5.55
A6 Soapstone Immortal	17.10	3.81	7.99	76.96	64.31	3.37
A7 Zun wine vessel	17.20	10.70	21.40	125.50	55.56	3.71
A8 Ting food vessel	18.70	17.60	17.60	129.43	76.70	3.76
A9 Soapstone Seal	19.60	5.84	5.84	22.34	82.82	2.77
A10 Lidded ritual ewer	25.00	22.50	22.20	110.84	76.35	3.22
A11 Ink Cake in Shape of Coiled Dragon	26.40	19.10	4.00	84.66	75.44	3.83
A12 Porcelain Baluster Vase	25.40	11.40	11.40	32.25	89.23	2.82
A13 Jade Bi Disc	28.90	28.90	0.32	44.98	73.84	3.13
A14 Eight Corners Case	31.00	27.00	27.00	200.63	90.88	4.22
A15 Blue and White Porcelain Vase	42.90	34.00	34.00	48.78	97.08	2.65
A16 Bronze Music Instrument	63.00	51.00	42.00	154.27	58.54	5.59
A17 Tri-coloured Camel	83.00	67.00	27.00	130.44	92.59	6.29
A18 Seated figure of bodhisattva Guanyin	98.43	57.27	64.48	127.94	79.13	3.94
A19 Gray Pottery Chiwen	152.00	99.00	83.00	203.25	81.93	6.29
A20 Eleven-Headed Guanyin	218.50	54.00	45.00	79.225	48.24	3.95

(2) user-defined distance to artifact (d) , measured from the edge of artifact to the camera along the Z axis;

(3) user-defined dimensions of the scaled artifact, including the height (H_a), width (W_a), and depth (D_a);

(4) users' eye level (EL), measured from the camera to the ground.

5.4 Participants

Twenty participants voluntarily signed up for the study, resulting in a dataset collected from 14 females and 6 males aged between 19 and 27 $(M = 22.4, SD = 2.76)$. All had normal or corrected to normal vision. Among the participants, 13 had moderate (5-100 hours) and 2 had extensive (>100 hours) experience in museum visiting, while 5 reported little to no experience (<5 hours). Regarding their VR experience, 9 participants reported little to no experience, 8 reported moderate experience, and 3 reported extensive experience. Additionally, 15 participants reported minimal experience in VR museum visiting and 5 reported moderate experience.

5.5 Results

We used IBM SPSS Statistics 26 for the data analysis. Table 2 shows the descriptive data. Given the large variance, we use the median value as default settings: pedestal height $H_p = 104\ cm$, distance to artifact $d = 92.31\ cm$, and artifact dimensions $H_a = 33\ cm, W_a = 22.62\ cm, D_a = 18.66\ cm$ (see Fig. 3).

Table 2: Descriptive table showing user-defined pedestal height (H_p), distance to artifact (d), and artifact scale size (H_a, W_a, D_a).

	Mean	**SD**	**Min**	**Median**	**Max**
H_p	94.46	30.54	0.00	104.00	144.00
d	114.99	78.18	28.57	92.31	516.04
H_a	35.30	15.92	9.00	33.00	122.00
W_a	24.25	12.56	2.90	22.62	72.35
D_a	20.85	14.07	0.14	18.66	82.12

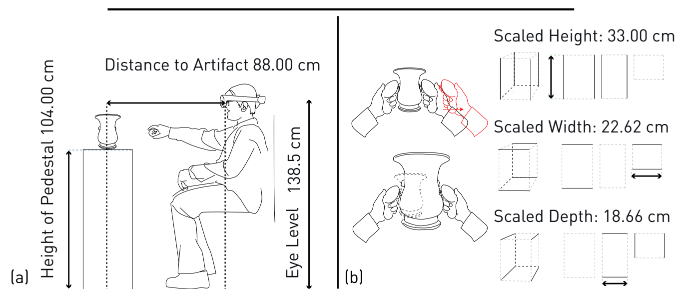

Fig. 3: Suggested default settings based on user-defined data for (a) fixed-position display and (b) handheld interaction with the artifacts.

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Table 3: Regression results for the prediction of pedestal height (H_p), distance to artifact (d), and scaled size of artifact (H_a, W_a, D_a).

	F	*sig.*	R^2	Constant	W	H	D	E	B	G	EL	H_p
H_p	88.32	$p < 0.001$	**0.61**	31.97	/	- 0.41	/	/	/	/	0.56	/
d	25.66	$p < 0.001$	**0.34**	106.08	/	0.56	/	/	/	/	0.63	-0.79
H_a	9.30	$p < 0.001$	0.14	43.45	/	0.11	/	/	/	/	-0.18	/
W_a	18.20	$p < 0.001$	0.25	44.56	0.47	-0.12	0.20	0.09	/	- 3.40	- 0.12	/
D_a	47.72	$p < 0.001$	**0.46**	48.63	-0.34	- 0.11	0.75	0.16	/	- 6.18	-0.12	/

Height of Pedestal (H_p). We conducted multiple regression analysis to test if the user's eye level (EL), artifact size (H, W, D), and detail richness (E, B, G) significantly predicted the optimal height of pedestal (H_p). The results indicated that the predictors explained 61% of the variance ($R^2 = 0.61, F(7, 392) = 88.32, p < 0.001$). It was found that the **user's eye level** (EL) and **artifact's height** (H) significantly predicted the optimal height of pedestal (H_p) ($p < 0.05$). We derive the prediction formula F1:

$$H_p = 0.56EL - 0.41H + 31.97 \tag{1}$$

Viewing Distance (d). A multiple regression analysis was run to test if the user's eye level (EL), artifact size (H, W, D), detail richness (E, B, G), and the pedestal height (H_p) significantly predicted optimal viewing distance (d). The results indicated that the predictors explained 34% of the variance ($R^2 = 0.34, F(8, 391) = 25.66, p < 0.001$). The **user's eye level** (EL), the **artifact's height** (H), and the **pedestal height** (H_p) significantly predicted the viewing distance (d) ($p < 0.05$). We derive the prediction formula F2:

$$d = 0.63EL + 0.56H - 0.79H_p + 106.08 \tag{2}$$

Handheld Size of Artifact (H_a, W_a, D_a). We conducted multiple regression analysis to predict the effects of the user's eye level (EL), artifact size (H, W, D), and detail richness (E, B, G) on the scaled height, width, and depth, respectively. The results showed that the scaled depth of artifact (D_a) had the highest proportion of variance (46%) that can be explained by the independent variables (see Table 3). Specifically, **user's eye level** (EL), **artifact's size** (H, W, D) and **detail richness** (E, G) significantly predicted the artifact size, $p < 0.001$. We derive the prediction formula F3:

$$\begin{aligned} D_a = &-0.12EL - 0.11H - 0.34W + 0.75D \\ &+ 0.16E - 6.18G + 48.63 \end{aligned} \tag{3}$$

6 Design of ResponsiveView

Based on the findings in Study 1, we developed ResponsiveView, which automatically adjusts pedestal height, facilitates optimized teleportation to the best viewpoint, and adapts appropriate artifact sizes for handheld interaction (see Fig. 4a).

6.1 Enhanced Teleportation and Manipulation

The following three features were implemented in ResponsiveView:

1. Personalized pedestal height. When users enter the VR museum, ResponsiveView automatically retrieves their eye level and the actual height of each artifact to configure personalized settings of pedestal heights using F1. Once initialized, these pedestal height settings will remain consistent.

2. Auto-predicted viewing distance. With the optimal pedestal height, the user's eye level, and the artifact height, the teleport hotspots were configured for each artifact based on the recommended viewing distance (d) from F2. By selecting the corresponding teleport hotspot, users can automatically move to the optimal viewpoint.

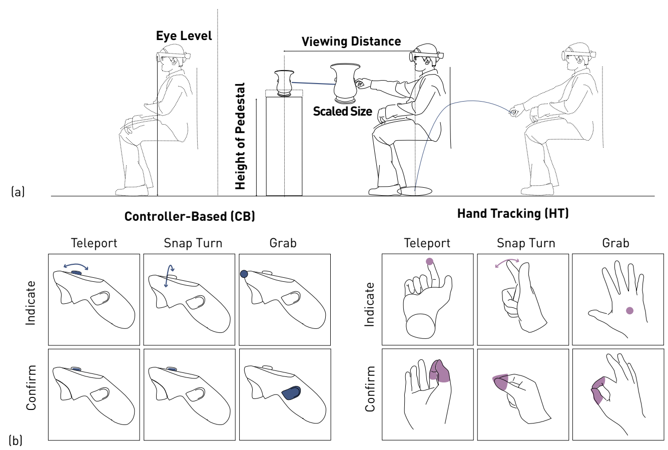

Fig. 4: Illustrations of (a) 3D artifact viewing in VR museum with ResponsiveView enabled, and (b) controller-based and hand tracking inputs.

3. Auto-predicted artifact size. Similarly, we used F3 to determine the optimal handheld size based on the user's eye level, and the artifact's dimensions and detail richness indicated by edge counts and gray contrast. This setup allowed for an adaptive size for close observations and natural interactions.

6.2 Implementing ResponsiveView with Different Inputs

An important part of 3D interaction design is choosing an appropriate set of inputs that allow the user to communicate with the application [4]. We select two input methods commonly used in current VR systems to apply and evaluate ResponsiveView.

Controller-based input. Tracked handheld controllers are common input devices for most VR HMDs [23, 39] (e.g., Meta Quest 2/3/ Pro, HTC Vive/Pro, Pico), typically featuring buttons, joysticks, and touchpads. One remarkable strength of controller-based input is its operation accuracy [39]. Fig. 4b (left) shows the use of ResponsiveView with controller-based inputs. Users can activate a ray to select a teleport hotspot by pushing the joystick forward. Horizontal movements of the joystick enable users to turn their views. Additionally, users can press the grip button to grab an artifact.

Hand tracking. Many VR platforms also support hand tracking input (e.g., Meta Quest 2/3/Pro, HTC Vive, Pico). Compared to controller-based input, hand tracking supports intuitive and nature interaction [39]. However, this method lacks accuracy, making hand tracking an area of ongoing research [33]. Fig. 4b (right) shows the use of ResponsiveView with hand tracking inputs. Users can point their index finger to the teleport hotspot to move, and point to the sides to turn their view. To indicate a grab selection, they aim their open palm at the target artifact. Users need to pinch their thumb and index finger to confirm their actions.

7 Study 2: Evaluating ResponsiveView

The second study aims to answer **RQ3**: *Does ResponsiveView enhance the viewing experience of 3D artifacts in VR museums?* It follows a within-subjects design with two conditions (baseline and ResponsiveView) to assess the effectiveness of our design with controller-based and hand tracking inputs, respectively.

7.1 Apparatus and Implementation

We conducted this study using the same hardware and software platforms as the previous study. The baseline condition was implemented according to existing guidelines for museum displays. Specifically, museums suggest different pedestal height ranges for general ($70-200\ cm$), small ($80-160\ cm$), and very small artifacts ($80-100\ cm$) [10]. A typical viewing distance of $105\ cm$ is also suggested in [41]. Table 4 shows the comparison of the two conditions.

Table 4: Comparative settings in the two conditions.

	Baseline	**ResponsiveView**
Height of pedestal	135/120/90 *cm* [10]	Determined by F1
Viewing distance	105 *cm* [41]	Determined by F2
Handheld size of artifact	Artifact's actual size	Determined by F3

Typically, responsive web design requires either manual checks or automated detection and modification tools [35]. However, since we introduced a novel responsive design for VR, no such tools are applicable. We manually assessed the responsive VR museum and discovered that artifacts A9, A11, and A13 have extremely thin depths (see Fig. 2), and applying F3 to them resulted in excessively large handheld sizes. Thus, we referred to the results in Table 3 to calculate the scaled width (W_a) of A11 and A13, and the scaled height (H_a) of A9.

7.2 Procedure and Tasks

Fig. 5a shows the experimental procedure. Participants were first informed of the purpose of the study and signed a consent form. After that, they were asked to fill in the demographic questionnaire that included information about their gender, and age, as well as their previous experience with museum visiting, VR use, and VR museums. The experimental session started with the tutorial scene to help them familiar with the controller-based and hand tracking interactions. After the tutorial, participants were asked to filled out Simulator Sickness Questionnaire (SSQ). Following this, participants completed an experimental task session. They then put off the VR headset and filled in the post-session questionnaires. A Latin Square Design was followed to counterbalance the sequential effects [6]. After the two sessions (baseline and ResponsiveView), they were asked to discussed their preferences and provided suggestions in an interview. The experiment took about 60 minutes in total.

For each experimental task session, participants visited an exhibition room containing ten artifacts (see Fig. 5b). To encourage participants' focus on the visual details of the artifacts, no other informational labels were provided for these. Participants were instructed to perform the following interactions for each artifact: (1) teleport to view and describe the artifact from the fixed-position display; (2) grab to view and describe it from the handheld display. Afterward, the participant was prompted to teleport to the next artifact, continuing this process until all ten artifacts had been viewed.

7.3 Data Collection and Analysis

System Logged Data. Our system logged objective data in the task sessions to evaluate the locomotion efficiency. Specifically, we recorded (1) **frequency of teleportation**: the total number of teleportation throughout the task; (2) **teleportation hover time**: the time taken to hover and select teleportation points; and (3) **frequency of snap turns**: the total number of snap turns taken during the task.

Questionnaire Measures. We included five subjective measures. (1) **Usability**, measured using the System Usability Scale (SUS) [7]. A threshold value of 68 indicates acceptable usability; (2) **User experience**, measured using the short version of the User Experience Questionnaire (UEQ-S) [29] on a 7-point Likert scale from -3 to 3; (3) **Engagement**, measured with four 5-point Likert scale questions from the Museum Experience Scale (MES) [27]; (4) **Task Load**, measured using the standard NASA Task Load Index [13] with six indicators: mental demand, physical demand, temporal demand, performance, frustration, and effort. The total score ranges from 0 to 100 [11]; (5) **Sickness**, measured using the Simulator Sickness Questionnaire (SSQ) [14] with 16 items for symptoms of nausea, oculomotor, and disorientation. These were rated on a 0-3 scale (none, slight, moderate, and severe).

Visual Information, Satisfaction and Preferences. We used the think-aloud method [8] to evaluate the visual information participants observed when viewing the artifacts and to collect participants' subjective ratings about the artifact displays. Specifically, we guided participants to evaluate the **visual information observed** in the front of the artifact, and when they were grabbing artifacts using their hands. In addition, they were asked to rate their **satisfaction with the fixed-position and handheld displays** (from 1 to 10). At the end of the experiment, participants discussed their **preferences** of the two conditions.

The data analysis was conducted in IBM SPSS Statistics. We assessed the distribution and homogeneity of variances of our data to help determine the statistical tests to use. Paired-samples t tests were applied for data that met the test assumptions, and Wilcoxon signed-rank test was used otherwise. We computed the effect size d for paired-samples t tests, with threshold values of 0.2, 0.5, and 0.8 representing small, medium, and large effects, respectively. The effect size r for Wilcoxon signed-rank test has threshold values of 0.1, 0.3, and 0.5 for the above-mentioned effect magnitudes. For qualitative data, we performed theme-based content analysis [26] on the transcriptions to group similar remarks into themes.

7.4 Participants

We conducted an a priori power analysis using G*Power software to determine the required sample size. With an effect size of 0.8 (indicating a medium to large effect), a significance level of 0.05, and a desired power of 0.8, the paired-samples t tests require a total sample size of 12 to provide sufficient statistical power.

This study involved 24 participants. Twelve participants (P3, P6-11, P13-17, 7 males and 5 females) between 19 and 28 years old ($M = 22.17, SD = 2.95$) used the controller-based input. Among them, 5 had moderate (5-100 hours) and 4 had extensive (>100 hours) experience in museum visiting, while 3 reported little to no experience (<5 hours). Regarding VR experience, 6 participants reported little to no experience, 5 reported moderate experience, and 1 reported extensive experience. Nine participants reported minimal experience in VR museum visiting and three reported moderate experience. Another twelve participants (P1-2, P4-5, P12, P18-24, 6 males and 6 females) between 19 and 27 years old ($M = 21.92, SD = 2.81$) used the hand tracking input. Among them, 8 participants reported moderate (5-100 hours) experience in museum visiting, 4 reported minimal (<5 hours) experience. Regarding VR experience, 6 participants reported little to no experience, and 6 reported moderate experience. All participants reported minimal experience in VR museum visiting.

7.5 Results

7.5.1 ResponsiveView with Controller Inputs

Locomotion Efficiency. Fig. 6 shows the analysis results. A paired-samples t test showed no statistically significant difference in the frequency of teleportation, $t(11) = 1.95, p = 0.078, d = 0.61$. In addition, a Wilcoxon signed-rank test showed no statistically significant difference in the teleportation hover time ($z = 1.57, p = 0.12, r = 0.34$). However, ResponsiveView demanded a lower frequency of snap turns than the baseline condition, $t(11) = 2.39, p = 0.036, d = 0.78$.

Usability and User Experience. Both the median and the mean scores of baseline and ResponsiveView fell within the suggested *acceptable* range of usability [7], while ResponsiveView showed *good* usability. A paired-samples t test showed significantly higher usability scores for ResponsiveView than the baseline, $t(11) = 2.35, p = 0.038, d = 0.99$. A Wilcoxon signed-rank test showed that user experience with ResponsiveView was significantly greater than the baseline,

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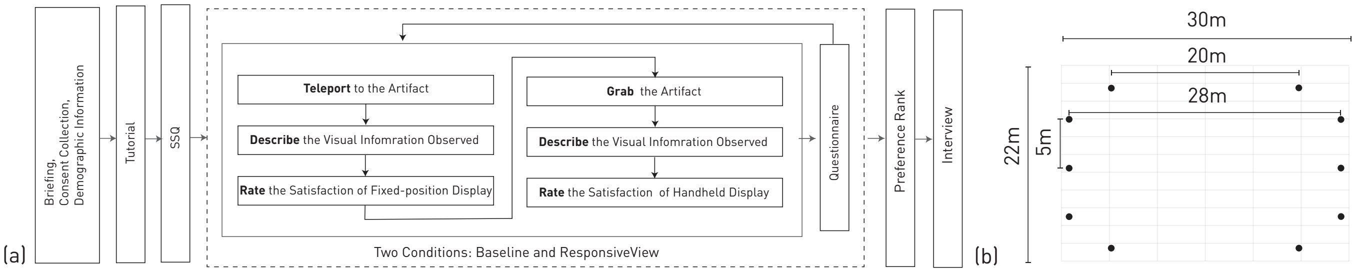

Fig. 5: (a) Experimental procedure for evaluating ResponsiveView. (b) The artifact layout in the VR museum environment.

$z = 2.50, p = 0.012, r = 0.31$. Significant differences were shown for the pragmatic quality ($z = 2.30, p = 0.022, r = 0.30$) and the hedonic quality ($z = 2.55, p = 0.011, r = 0.30$). Both were rated higher for the ResponsiveView.

Engagement and Satisfaction. We observed no significant difference in overall engagement, $z = 1.66, p = 0.096, r = 0.24$. However, Wilcoxon signed-rank tests showed significant differences in the perceived satisfaction of the fixed-position display ($z = -3.58, p < 0.001, r = 0.22$) and the handheld display ($z = -3.70, p < 0.001, r = 0.07$). Both were rated higher for the ResponsiveView. Compared to the baseline, all participants preferred ResponsiveView with controller-based inputs.

Negative Feelings. We observed no significant difference in overall perceived task load between two conditions, $t(11) = 2.39, p = 0.089, d = 0.57$. No significant difference was shown in perceived mental demand ($t(11) = 1.60, p = 0.089, d = 0.54$), physical demand ($t(11) = 1.71, p = 0.110, d = 0.21$), temporal demand ($z = 0.34, p = 0.735, r = 0.11$), effort ($t(11) = 1.54, p = 0.15, d = 0.46$), or frustration ($z = 1.90, p = 0.058, r = 0.34$). However, the performance was perceived significantly greater for ResponsiveView, $t(11) = 2.30, p = 0.042, d = 0.69$. Wilcoxon signed-rank tests showed no statistically significant difference in the reported symptoms of nausea ($z = 0.74, p = 0.461, r = 0.00$), oculomotor ($z = 0.41, p = 0.680, r = 0.01$), disorientation ($z = 0.38, p = 0.705, r = 0.07$), or the overall motion sickness ($z = 0.43, p = 0.670, r = 0.07$).

7.5.2 ResponsiveView with Hand Tracking Inputs

Locomotion Efficiency. A paired-samples t test showed no significant difference in significant difference in the frequency of teleportation ($t(11) = 0.40, p = 0.697, d = 0.21$). However, a Wilcoxon signed-rank test showed a significant difference in the teleportation hover time ($z = 2.28, p = 0.023, r = 0.36$). Participants needed less teleportation hover time when using the ResponsiveView. No statistically significant difference was found in the frequency of snap turns ($z = 0.79, p = 0.432, r = 0.05$).

Usability and User Experience. Overall, ResponsiveView showed a *good* usability, while the baseline was *acceptable*. A paired-samples t test showed no significant difference in usability scores, $t(11) = 1.68, p = 0.067, d = 0.67$. Similarly, no significant difference was observed in the evaluation of user experience, $t(11) = 2.03, p = 0.067, d = 0.55$. Their differences in the pragmatic quality ($t(11) = 1.36, p = 0.106, d = 0.55$) and the hedonic quality ($t(11) = 1.87, p = 0.088, d = 0.47$) were insignificant.

Engagement and Satisfaction. A paired-samples t test showed that participants were more engaged in ResponsiveView than the baseline condition, $t(11) = 2.45, p = 0.033, d = 0.68$. In addition, Wilcoxon signed-rank tests showed significant differences in user satisfaction of the fixed-position display ($z = -4.294, p < 0.001, r = 0.29$) and the handheld display ($z = -3.75, p < 0.001, r = 0.23$). Both were rated higher for the ResponsiveView. For hand tracking input, eleven participants preferred ResponsiveView while one participant preferred the baseline, since the teleport hotspots are hard to select.

Negative Feelings. We observed no significant difference in overall perceived task load, $t(11) = 1.66, p = 0.125, d = 0.41$. No significant difference was shown in perceived mental demand ($t(11) = 0.49, p = 0.636, d = 0.09$), physical demand ($t(11) = 0.45, p = 0.659, d = 0.15$), temporal demand ($z = 1.56, p = 0.119, r = 0.18$), performance ($t(11) = 1.54, p = 0.088, d = 0.29$), or effort ($t(11) = 1.54, p = 0.151, d = 0.46$). However, participants perceived significantly greater frustration in the baseline condition, $t(11) = 2.43, p = 0.045, d = 0.45$. Wilcoxon signed-rank tests showed no statistically significant difference in the reported symptoms of nausea ($z = 0.26, p = 0.792, r = 0.17$), oculomotor ($z = 0.14, p = 0.885, r = 0.15$), disorientation ($z = 1.67, p = 0.096, r = 0.17$), or the overall motion sickness ($z = 0.77, p = 0.439, r = 0.06$).

7.5.3 Visual Information Observed

With the fixed-position display, participants have reported visual information about artifacts' shape, color, and material. Some subtle elements, such as detailed patterns and decorations were rarely reported. However, such detailed information was frequently reported when using the handheld display. Participants responded positively on how they can grab artifact in hand and rotate it to fully view the artifact, which allowed for richer visual information observed.

7.5.4 Think-Aloud and Interviews

We analyzed the transcriptions from the study and there were some themes emerged from the analysis.

Observed information not visible in real museums ($n = 24$). When the artifact is of an appropriate size, all participants could examine and reported details from the back, bottom, top, and even the interior of the artifacts, which are typically not accessible in real museums. For example, P17 noticed the imperfections behind artifact A20 and remarked that he would never have the opportunity to see such visual details in a real museum. P20 added *"This is the first time I've seen a cultural relic like this. I can see the collection label on the bottom and the damage on the back. Honestly, I'm shocked."*

Ease of teleportation ($n = 9$). Participants reported difficulty to accurately teleport to face the artifact in the baseline condition. P24 noted, *"When I was trying to move to the front viewpoint, I needed to make some slight adjustments. It was difficult when I got close to the artifact."* With ResponsiveView, participants noted that teleport hotspots were well-aligned with the artifact's display, positioning it centrally in their field of view with a reasonable distance. They found it significantly enhanced their viewing experience.

Responsive handheld size contributed greatly to the viewing experience ($n = 24$) Participants found it difficult to view anything when the original artifact was large in size (e.g., A18, A19, A20) in the baseline condition. P20 mentioned that in such cases, he preferred not to grab the artifact but to only observe its front. P24 even screamed out when she attempted to grab a large artifact (A16), stating *"The monster just came straight at me. I felt my whole body was inside of it. I can't see anything."* Additionally, some delicate artifacts were also not fully viewable by participants. On the other hand, participants expressed a highly positive attitude toward the responsive handheld size of the artifacts. For instance, when P13 held the large artifact A20 (see Fig. 7, a1-a2), she remarked that the system provided a comfortable handheld size, allowing her to view the entire artifact without missing any details. Similarly, when P14 held artifact A4 which was scaled up (see Fig. 7, b1-b2), he praised this feature, comparing it to using a magnifying glass in the real world.

Difficulty with hand tracking inputs ($n = 6$). While using hand tracking input, four participants (P5, P19, P21, P24) reported difficulty

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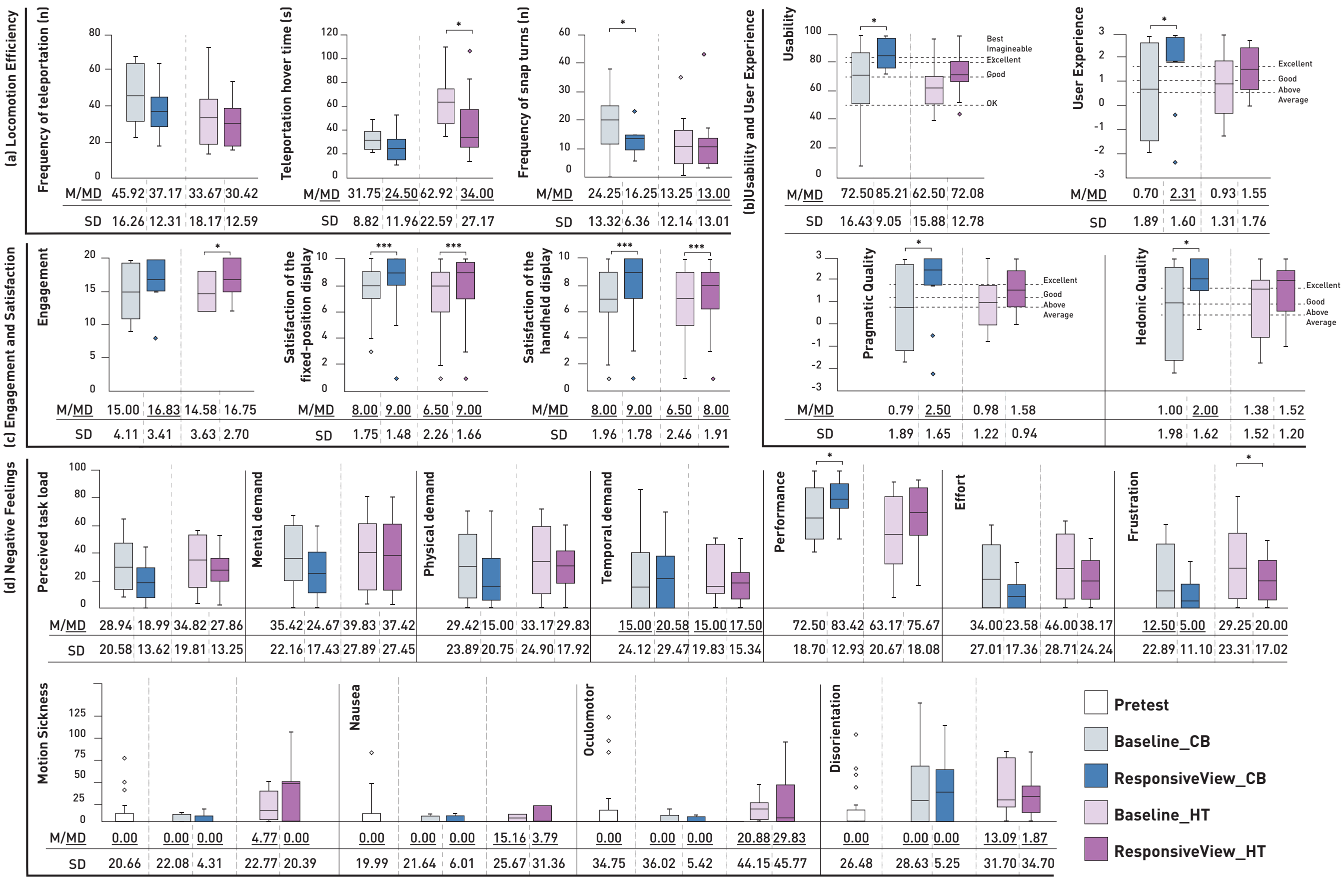

Fig. 6: Boxplots and descriptive tables with means (M), medians (MD), and standard deviations (SD) showing the 3D artifact viewing experience in aspects of (a) locomotion efficiency, (b) usability and user experience, (c) engagement and satisfaction, and (d) negative feelings. CB = controller-based, HT = hand tracking.

Fig. 7: Comparative views showing the act of grabbing a large artifact (A20) in the (a1) baseline condition and (a2) the ResponsiveView condition with the size scaled down. For smaller artifacts (e.g., A4), (b1) the baseline displays its actual size, while (b2) the ResponsiveView showed an enlarged view with enhanced clarity.

with hand tracking inputs. For example, P19 expressed frustration at being unable to accurately reposition herself to a suitable viewing point. The need to pinch may have resulted in a slight deviation from the intended confirming position. In addition, participants faced issues with false positives, unintentionally grabbing an artifact when they meant to teleport. They also encountered interruptions during handheld observation. For example, an artifact may drop when users rotate the pinch gesture - this is likely due to errors in dynamic gesture recognition. With ResponsiveView, participants the hover time for teleportation was significantly reduced, resulting in less sense of frustration and improved satisfaction. Still, P20 and P24 experienced arm fatigue during their second experimental session.

Ergonomic issues with the headset ($n = 3$). Three participants (P1, P20, and P24) expressed discomfort with having to look down to view some artifacts. For example, P24 commented that *"I felt like my headset was going to fall off, so I had to lift my head to keep it secure, but at the same time I had to look down, which was weird."*

Mismatched mental model ($n = 2$). P1 and P20 reported unnatural interactions with large artifacts. P1 noted, *"Some artifacts looks very heavy, but when I picked it up, I couldn't feel any weight."* Similarly, P20 noted while grabbing A19, *"This isn't something I should be able to lift with just my fingers. It feels like I need both hands to lift it up."*

8 Discussion

Study 1 explored ways to determine the optimal display (pedestal height and viewing distance) for fixed-position views (**RQ1**) and to determine the optimal size for handheld interaction with 3D artifacts (**RQ2**). We collected user-defined data and suggested settings corresponding to the guidelines for physical museums. In addition, we showed that the optional viewing settings in VR museums can be accurately modeled. Specifically, the *pedestal height* can be determined by the user's eye level and the artifact's height; the *viewing distance* can be determined by the user's eye level, the artifact's height, and the pedestal height; the *handheld size* can be determined by the user's eye level, the artifact's dimensions (height, width, and depth), and its detail richness (edges and contrast). These results and findings answered **RQ1** and **RQ2**, providing a framework for enhancing viewing experience with 3D artifacts in VR museums. Guidelines for physical museums are typically defined by a fuzzy range (e.g., large, small), and it is often impractical or costly to customize display cases for each artifact. However, our work demonstrated the feasibility of customized design for each individual artifact based on specific data dimensions (e.g., height in). These findings also pave the way for future research aimed at improving the responsive design in VR.

Study 2 answered **RQ3** by showing that compared to the baseline condition, ResponsiveView demonstrated improved users' viewing experience in VR museums with both controller-based and hand tracking input techniques. Results show that ResponsiveView with controller-based input led to improvements in locomotion efficiency (snap turns), usability and user experience, user satisfaction, and the sense of performance. We did not find significant differences in the frequency of teleportation, teleportation hover time, or user engagement in VR museums between two conditions. The results also indicate that with hand tracking input, ResponsiveView enhanced locomotion efficiency (less teleportation hover time), user engagement and satisfaction, and reduced the sense of frustration. In addition, ResponsiveView showed greater usability and user experience based on the benchmark results. We did not find significant differences in the frequency of teleportation or snap turns between two conditions.

The findings highlighted the effectiveness of ResponsiveView in addressing the key challenges faced in 3D artifact viewing in VR museums, offering practical implications for implementing VR museum settings. The responsive design enhanced users' viewing experience by improving user navigation movements and artifact manipulations. By effectively modeling the pedestal height, viewing distance, and handheld size, the design facilitated a more comfortable and engaging experience. As existing literature has rarely explored design guidelines for 3D artifact viewing in VR museums, our research helps bridge this gap. The study showcases the effectiveness of ResponsiveView for 3D artifacts viewing in VR museums and provides valuable insights into the advancement of responsive technique design based on controller-based and hand tracking interactions. The findings from our study enable VR museum curators and designers to address the fundamental design considerations related to movements and manipulations and to optimize the presentation of artifacts. From our findings, we derive a set of design recommendations (R) for future techniques in VR museums or other virtual environments with 3D object display.

DR1 For VR museums necessitating fixed parameters, we suggest a pedestal height of 104 *cm*, a viewing distance of 92 *cm*, and a handheld size around $33 \times 23 \times 19$ $(H \times W \times D)$.

DR2 Whenever possible, provide responsive (adjustable) settings for different users and environments. Measure users' eye levels (EL) as well as the objects' dimensions (H, W, D) and detail richness (E, G) in the environment. Specifically,

- use `F1`: $H_p = 0.56EL - 0.41H + 31.97$ to determine the *height of pedestal*,
- use `F2`: $d = 0.63EL + 0.56H - 0.79H_p + 106.08$ to determine the *viewing distance*, and
- use `F3`: $D_a = -0.12EL - 0.11H - 0.34W + 0.75D + 0.16E - 6.18G + 48.63$ to calculate the scaled depth of the *handheld artifact*. Do manual check and consider the scaled height or width as alternatives.

DR3 For locomotion, prioritize noticeable and easy-to-select teleport hotspots with a preset viewing distance. This enhances locomotion efficiency, allowing artifacts to appear in the center of the users' view.

DR4 Implement locomotion techniques that enable users to make slight positional adjustments around the pedestal, such as steering. This finding aligns with previous research [44].

DR5 Unlike guidelines for physical museums that suggest positioning artifacts slightly below visitors' eye level [41], we advise against having users bow their heads in VR museums. This recommendation takes into account the ergonomic challenges associated with VR HMDs, as this type of head motions can lead to discomfort.

DR6 Despite ResponsiveView demonstrating an elevated viewing experience for both controller-based and hand tracking inputs, controller-based inputs still outperformed hand tracking. This is consistent with the findings in [39]. Thus, we recommend using controller-based inputs, whenever possible, for VR museums based on current commercially available solutions.

DR7 Current hand tracking techniques still face challenges regarding precision in control. If implemented, it is crucial to implement strategies to prevent unintended actions. For instance, artifacts should remain being grabbed until a specific release action is intentionally executed. Modeling the activation range of actions may also help avoid false positives.

9 Limitations and Future Work

Our study has some limitations. First, to facilitate quick understanding and implementation by non-graphics professionals, such as museum curators and designers, we opted to utilize low-level features of the artifacts that are easily accessible, such as their dimensions and the detail richness. While this approach allowed us to streamline the process, it limited our inclusion to only the fundamental characteristics of the artifacts. Notably, we did not incorporate additional contextual information, such as background details or the width and depth of the pedestal. Second, while the coefficient of determination for predicting pedestal height was relatively strong ($R^2 = 0.61$), it was weaker for the best viewing distance ($R^2 = 0.34$) and the handheld size ($R^2 = 0.46$). Future work could refine the models by considering more influencing factors and increasing the sample size of training data set. Third, it is important to note that our sample predominantly consisted of young adults. Although this group of users represents the primary groups for VR museums and the target users in promotional efforts [9, 15], it may limit the generalizability of our findings to other age groups. Fourth, our comparisons in the second study were more exploratory than confirmatory. This exploratory nature suggests that while we gathered valuable insights, further research is needed to validate our findings and potentially uncover deeper relationships between variables. Lastly, users reported experiencing ergonomic discomfort with the commercial headset we used, highlighting the necessity for further ergonomic considerations during extended viewing sessions. Future research could also build on the current study to model user behaviors in VR. For instance, it would be valuable to explore the appropriate social, personal, and intimate distances for interpersonal communication and social interactions in VR. While Hall [12] defined proximity ranges in the physical world, it remains unclear whether these perceptions hold true in a VR environment. Other scenarios such as virtual shopping and assembly could also benefit from responsive designs that augment users' capabilities in movements and manipulation.

10 Conclusion

In this paper, we presented two studies focusing on improving 3D artifact viewing experience in Virtual Reality (VR) museums. The first study explored the optimal display (pedestal height and viewing distance) for fixed-position 3D artifact viewing and the optimal size for handheld 3D artifact viewing in VR museums. We modeled user-defined settings and proposed three predictive formulas that can determine the pedestal height, the optimal viewing distance, and the handheld size of artifact. Based on the results, we proposed a responsive design, ResponsiveView, aiming to improve the locomotion and interactions associated with viewing 3D artifacts in VR museums. An evaluation study was conducted to understand whether ResponsiveView enhance the viewing experience of 3D artifacts in VR museums. Our results showed its positive effects on both controller-based and hand tracking inputs. Participants' feedback during the experiment also indicated its strength in facilitating teleport movements and artifact manipulations. Furthermore, we formulated design recommendations for 3D artifact viewing in VR museums. Further work can build upon those guidelines, validating and refining the design through user behavior modeling to continually improve responsive design in VR museums.

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