

# Interactive virtual reality for evaluating affective responses in memorial transition spaces: a pilot feasibility study

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## Abstract

Transition spaces at the end of trauma-memorial exhibitions provide settings for reflection and commemoration after exposure to emotionally demanding content. We developed and pilot-tested an interactive virtual reality (VR) protocol for evaluating these spaces through spatial exploration and commemorative participation. Three multi-attribute prototypes were developed for the terminal hall of the Memorial Hall of the Victims in the Nanjing Massacre by Japanese Invaders. Twelve participants each experienced one prototype through self-paced seated navigation and virtual flower placement. We recorded wearable electroencephalography (EEG) indices during VR exposure. Afterward, participants completed the Positive and Negative Affect Schedule, the State-Trait Anxiety Inventory state subscale, and an exploratory restorativeness questionnaire. An operator dashboard supported live monitoring and participant-level data management. All participants completed the protocol, yielding complete questionnaire and EEG-index datasets. Descriptive comparisons showed higher state anxiety for Prototype 1 than for Prototypes 2 and 3 (Hedges'  $g = 0.91-1.17$ ). Prototype 3 had higher mean positive-affect and perceived-restorativeness scores than Prototype 2, alongside higher negative affect. The pilot demonstrates the operational feasibility of the protocol for early-stage design evaluation.

**Keywords:** Immersive virtual reality; Electroencephalography (EEG); Perceived restorativeness; Memorial architecture; Architectural design evaluation

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## 1. Introduction

### 1.1. Memorial transition spaces and visitor experience

The design of exhibition spaces in trauma memorials must accommodate visitors' emotional needs while preserving the gravity of the history presented (Stone and Sharpley, 2008; Wagoner and Brescó, 2022; Brescó de Luna and Wagoner, 2024). This concern is particularly relevant at the end of the exhibition sequence, where visitors prepare to leave after encountering historical testimony. The final space, referred to here as the "tail-hall", provides a setting for reflection and commemoration. Its design must therefore relate the closing stage of the visit to the historical narrative while allowing visitors to engage with what they have encountered in their own way. A related design intention is evident at Yad Vashem, where the sunken, open-air courtyard at the end of the museum campus route was conceived as a "decompression chamber" (Lu, 2017). In this design, a distinct spatial setting is assigned to the closing stage of the visit, bringing emotional transition into the organization of the museum route.

This study focuses on designs for the tail-hall (Areas 57–60) of the Memorial Hall of the Victims in the Nanjing Massacre by Japanese Invaders. This space supports the transition from historical testimony toward reflection and remembrance. Visitor studies at this museum document heterogeneous and culturally mediated affective responses to the exhibition (Cui et al., 2020; Xie and Sun, 2018).

These varied emotional responses need to be considered alongside visitors' engagement with the space. Research on memorial design examines how material features create opportunities for exploration and commemorative participation (Wagoner and Brescó, 2022). In the designs examined here, such participation takes the form of virtual flower placement. We therefore evaluate the spatial setting and the commemorative activity together, considering perceived restorativeness alongside positive and negative affect and state anxiety.

### 1.2. Spatial design and affective assessment in VR

Environmental psychology provides a theoretical basis for examining the relationship between spatial settings, affective responses, and perceived restorativeness. Stress recovery theory addresses affective and physiological

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recovery following stress (Ulrich et al., 1991), while attention restoration theory concerns the renewal of directed attention (Kaplan, 1995). For architectural evaluation, the corresponding question is how particular features of an interior relate to these responses. Neuroarchitecture reviews have examined enclosure, geometric form, material, daylight, and overhead-plane conditions in this context (Bower et al., 2019; Attaianese et al., 2025; Assem et al., 2023). Studies of geometric form provide a specific example: comparisons of sharp and curved contours have identified differences in self-reported and neural responses (Shemesh et al., 2017, 2022; Coburn et al., 2017; Vartanian et al., 2013), while mobile EEG research has related interior geometry to brain activity during walking (Banaei et al., 2017).

Immersive virtual reality (VR) provides a way to investigate these design–response relationships through controlled comparisons of spatial designs (Chamilothori et al., 2019; Yin et al., 2019). Within these experiments, self-report and physiological measures offer complementary accounts of participants' responses (Bower et al., 2019; Mostafavi, 2022). For example, research on spatial openness has combined EEG, eye tracking, and electrodermal activity with psychological measures to examine stress and comfort (Gao et al., 2025). Related applications have assessed biophilic elements in hospital settings (Liu and Lee, 2026) and daylight illuminance in offices (Payedar-Ardakani et al., 2024).

The choice of measures is only part of the experimental design; exposure formats also differ in how much control participants have over exploration and interaction. A systematic review of architectural VR-and-EEG studies found that 65% used seated exposure, sometimes allowing controller-based movement or tasks, whereas 15% involved physical walking (Taherysayah et al., 2024). A review of neuroarchitecture measurement methods identified the predominance of passive observation as a methodological gap (Jaberi et al., 2026). Movement and interaction are relevant to the experience of a virtual place (Slater, 2009; Kalantari et al., 2021; Shemesh et al., 2026), but bodily movement also complicates EEG recording (Taherysayah et al., 2024; Djebbara et al., 2019). For early-stage evaluation of memorial interiors, the practical challenge is to let participants explore a spatial proposal and perform a meaningful commemorative action within a procedure that supports physiological recording.

### 1.3. Research gap and rationale

Restorative and neuroarchitectural VR research has focused largely on offices, healthcare and educational spaces, and biophilic or natural environments (Taherysayah et al., 2024; Jaberi et al., 2026; Attaianese et al., 2025). Studies in these settings have combined VR exposure with physiological recording and post-exposure self-report (Li et al., 2023; Da et al., 2024; Tashiro and Harada, 2025). Less is known about implementing such assessments in trauma-memorial interiors, where exploration and commemorative participation form part of the experience being evaluated. Before an interactive VR protocol is used for larger comparisons of tail-hall designs, a pilot study can establish whether participants complete the sequence, whether the planned participant-level data can be obtained, and which aspects of the procedure require refinement.

### 1.4. Objectives

We developed and pilot-tested an interactive, multimodal VR protocol for the early-stage evaluation of memorial transition-space designs. Seated participants navigated at their own pace using a hand controller and natural head tracking and completed a virtual chrysanthemum-placement task that triggered a lamp-lighting response. The protocol combined wearable EEG recording, post-exposure questionnaires, and an operator dashboard for monitoring and participant-level data management.

The primary aim was to assess operational feasibility by examining protocol completion, the availability of questionnaire and EEG-index data, and implementation issues. Secondary exploratory analyses described post-exposure affect, perceived restorativeness, and whole-session EEG indices across three multi-attribute prototypes. These analyses served two purposes: prototype comparisons identified design questions for larger studies, while cross-modal associations informed the selection of measures for subsequent evaluations.

## 2. Methods

Sessions were conducted on 23–24 May 2026 in a laboratory room at the School of Social and Behavioral Sciences, Nanjing University. Figure 1 summarizes the experimental protocol and its three parallel data channels. All between-group differences are reported as effect-size estimates (Section 2.6).

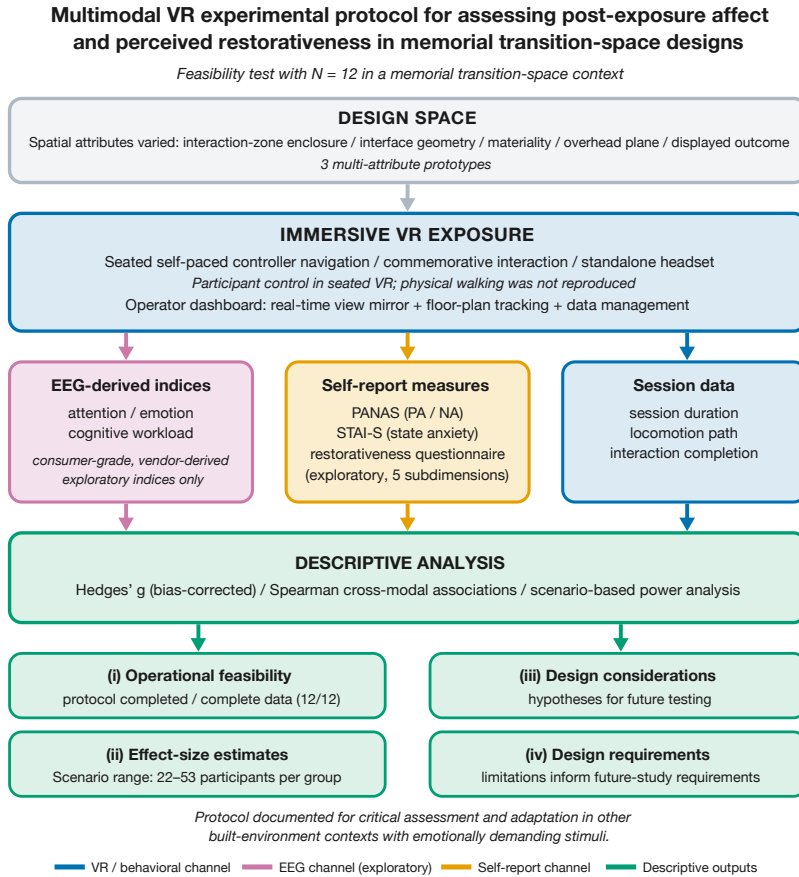


Figure 1: Multimodal experimental protocol for VR-based evaluation of post-exposure affect and perceived restorativeness in designs for memorial transition spaces ( $N = 12$ ). The protocol includes three parallel data channels: EEG-derived indices, self-report measures, and session data. These data support descriptive effect-size and cross-modal association analyses. Sample-size scenarios use conventional assumed effects (Section 3.5).

## 2.1. Participants

We recruited twelve students from the School's Department of Psychology as a convenience sample, with a relatively homogeneous disciplinary background. None had a background in architecture, environmental art, interior design, or fine arts. Professional design training can shape evaluative responses (Shemesh et al., 2017); excluding these backgrounds helped limit variation in formal design training within the sample. We also excluded individuals who reported a predisposition to motion or simulator sickness. Of the twelve participants, nine were postgraduate students and one was an undergraduate student (two did not report their educational level). Nine were women and three were men. Ten reported ages between 23 and 37 years ( $M = 28.0$ ), and two did not report their age. The resulting group compositions were three women and one man (Prototype 1), two women and two men (Prototype 2), and four women (Prototype 3).

All participants provided verbal informed consent before taking part. Using a standardized script in each participant's first language, the operator explained the study purpose, the non-invasive VR and EEG equipment, the procedure, and the inclusion of historical footage related to the Nanjing Massacre that some viewers could find distressing. Participants were told that participation was voluntary, that they could pause or withdraw without consequence, and that their data would be de-identified. Verbal agreement was witnessed by the operator and recorded in the session log. Written signatures were not collected. The consent procedure and its documentation were included in the subsequent ethics submission. All records were anonymized; participants are identified here only by codes P01–P12.

Following completion of data collection, the protocol was submitted to the Nanjing University Psychology Ethics Committee for retrospective ethical review. The committee approved the protocol on 24 July 2026 (approval no. NJUPSY202607020).

## 2.2. Study design and spatial prototypes

We used a between-subjects design with four participants allocated to each prototype. The operator made these assignments at the time of testing without a pregenerated randomization sequence. The three prototypes were developed as contrasting combinations of spatial attributes and are summarized in Table 1 and illustrated in Fig. 2.

**Table 1**

Attribute combinations of the three tail-hall prototypes.

| Prototype | Interface geometry / material | Commemorative interaction area enclosure | Overhead plane          | Displayed outcome                |
|-----------|-------------------------------|------------------------------------------|-------------------------|----------------------------------|
| 1         | sharp-edged timber            | enclosed                                 | present (with skylight) | individual outcome               |
| 2         | sharp-edged stone             | open                                     | absent                  | preconfigured collective outcome |
| 3         | curved stone                  | open                                     | absent                  | individual outcome               |

The participant action was identical across prototypes: placing a virtual chrysanthemum triggered a lamp-lighting response. Prototypes 1 and 3 then displayed an individual outcome, whereas Prototype 2 displayed a preconfigured collective arrangement. The prototypes varied on several attributes simultaneously, so each contrast represents an attribute combination. Prototypes 2 and 3 share material, enclosure of the commemorative interaction area, and overhead-plane condition, but differ in interface geometry (sharp-edged vs. curved) and displayed outcome (preconfigured collective vs. individual).

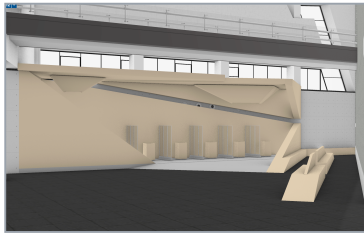
## 2.3. VR environment and the operator dashboard

We modeled the three prototypes in Rhinoceros 7 using CAD drawings authorized by the museum. The three virtual environments were implemented within a single real-time interactive application in Unity 2022.3.31f1 (2022 LTS) using the Universal Render Pipeline and OpenXR. The application was deployed as a standalone Android package on a PICO 4 Ultra Enterprise head-mounted display (HMD). The application used single-pass instanced stereo rendering at a render scale of 1.0, without foveated rendering or multisample anti-aliasing. Device logs recorded a per-eye render resolution of  $1920 \times 1920$  pixels and an approximate field of view of  $104^\circ$ . In a 450-frame performance sample, the application maintained 90 frames/s (mean frame time 11.1 ms), and no sampled frame exceeded the 16.7-ms threshold corresponding to 60 frames/s.

The HMD used inside-out six-degree-of-freedom tracking with a floor-level tracking origin and no artificial camera-height offset, thereby preserving each seated participant's eye height. Virtual movement and interaction were controlled with the right-hand controller. The right thumbstick's vertical axis controlled forward and backward movement at 2.2 m/s; lateral strafing and flight were disabled, and gravity was enabled. The thumbstick's horizontal axis controlled continuous smooth turning at  $45^\circ/\text{s}$ , with acceleration and deceleration set to 2.5 and a thumbstick dead zone of 0.18. The left controller's ray and interaction components were disabled. No vignette, field-of-view mask, or tunneling effect was applied. A Unity CharacterController prevented wall penetration (radius 0.30 m, height 1.65 m, step offset 0.10 m, maximum traversable slope  $45^\circ$ ).

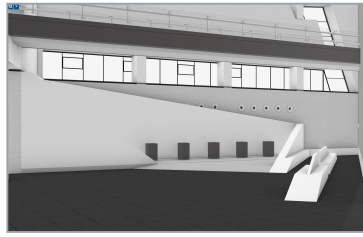
All prototypes used the same environmental-lighting configuration, with no prototype-specific artificial light source. Only Prototype 1 included an overhead plane above the commemorative interaction area; it occluded part of the shared environmental illumination, whereas the commemorative interaction areas in Prototypes 2 and 3 remained open above. The overhead-plane condition and scene brightness therefore varied together, and the scenes were not photometrically calibrated.

## Three tail-hall prototypes and their attribute combinations



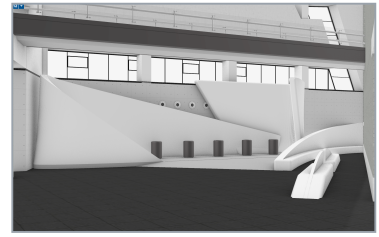
**Prototype 1**

Sharp-edged timber · enclosed interaction zone · overhead plane with skylight · individual outcome



**Prototype 2**

Sharp-edged stone · open interaction zone · no overhead plane · preconfigured collective outcome



**Prototype 3**

Curved stone · open interaction zone · no overhead plane · individual outcome

| Prototype | Interface geometry / material | Interaction-zone enclosure | Overhead plane          | Displayed outcome                |
|-----------|-------------------------------|----------------------------|-------------------------|----------------------------------|
| 1         | Sharp-edged timber            | Enclosed                   | Present (with skylight) | Individual outcome               |
| 2         | Sharp-edged stone             | Open                       | Absent                  | Preconfigured collective outcome |
| 3         | Curved stone                  | Open                       | Absent                  | Individual outcome               |

*Green cells: attributes that differ between Prototypes 2 and 3 (most comparable contrast).*

*All prototypes used the same action: place a virtual chrysanthemum, followed by a lamp-lighting response.*

Figure 2: The three multi-attribute tail-hall prototypes used in this feasibility study (top) and their attribute combinations (bottom). Prototypes 2 and 3 differ in interface geometry and displayed outcome, making them the most comparable pairwise contrast (highlighted cells); their contrast combines these two attributes.

Figure 3 shows the architecture linking the VR application, EEG acquisition, and operator dashboard. We developed a custom operator dashboard (a FastAPI/WebSocket web application) with four functions: (i) a live mirror of the participant's VR view for verbal guidance; (ii) a live floor-plan display of the participant's position and heading within the VR environment; (iii) administration and recording of the post-exposure questionnaires; and (iv) participant-level data management and export. EEG acquisition ran independently in the manufacturer's software. After export and offline analysis, the EEG-derived records were linked to the corresponding participant and session record in the dashboard's SQLite database. The dashboard panels marked MOCK (heart-rate variability, eye tracking, and electrodermal activity) were inactive demonstration panels for planned extensions.

## 2.4. Multimodal measures

### 2.4.1. EEG-derived indices

EEG signals were recorded with a consumer-grade dry-electrode EEG headband (TanXi Brain Cognitive Assessment Device; talkingBrain / Tanke Bairui Technology, Beijing, China), operated through the manufacturer's companion software. The ring-shaped headband has five dry electrodes positioned approximately over the prefrontal and temporal regions (FP1, FP2, FPz, and bilateral temporal sites), referenced to two ear-clip electrodes. The software outputs three proprietary indices (attention, emotion, and cognitive workload) at one value per second (1 Hz); the vendor does not disclose the underlying raw-EEG sampling rate. These dimensionless scores use undisclosed scales. In this sample, the attention index was non-negative (participant means  $\approx 0.9$ – $7.7$ ), the emotion index was signed (means  $\approx -1.1$  to  $+4.0$ , with more negative values indicating a more negative affective state), and workload values clustered near zero ( $\approx \pm 0.002$ ; Section 3.3). The proprietary algorithm and the known fidelity constraints of consumer-grade EEG limit construct-level interpretation (Sabio et al., 2024; Ratti et al., 2017); we therefore use the indices as supplementary physiological measures alongside self-report. Because the device operated independently from the VR system, the recording contained no in-VR event markers.

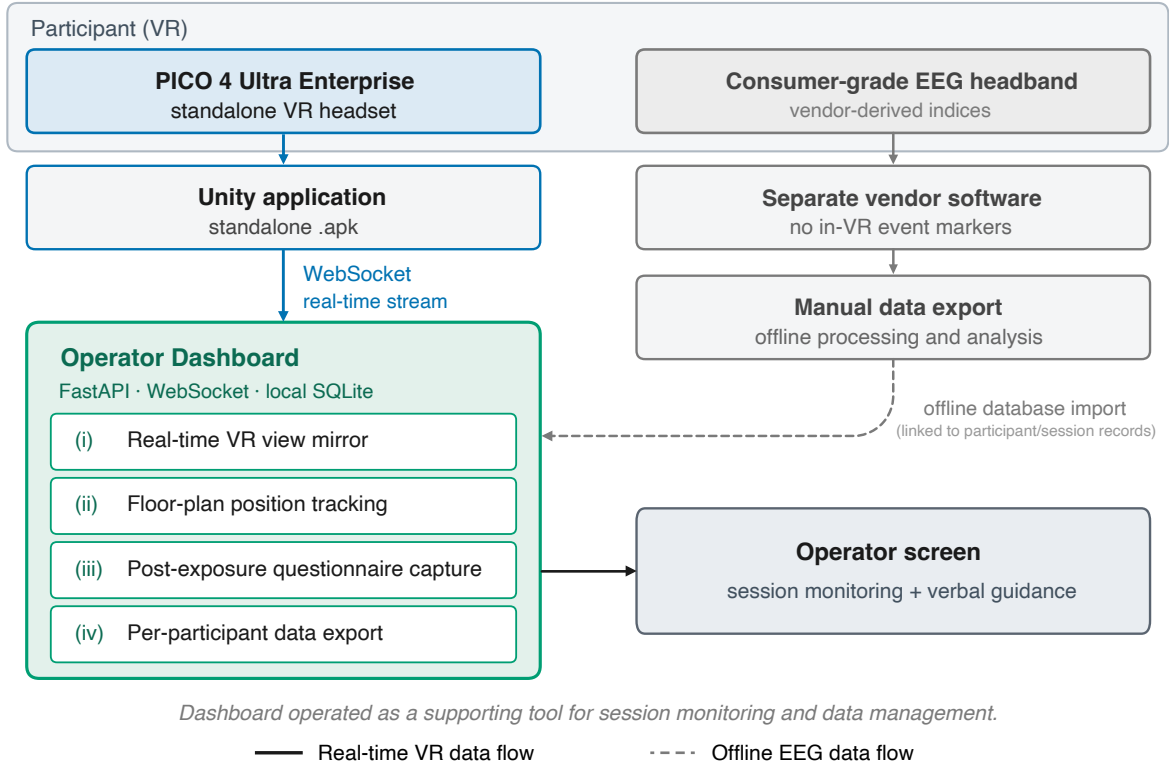
**System architecture: VR delivery, multimodal acquisition, and operator dashboard***Single-session pilot setup (N = 12). EEG was processed offline before dashboard import.*

Figure 3: System architecture. VR data streamed to the operator dashboard in real time (solid path). EEG was acquired in separate vendor software, exported and analyzed offline, and then imported into the dashboard database and linked to the corresponding participant and session record (dashed path); no shared in-VR event markers were available.

#### 2.4.2. Self-report scales

After VR exposure, participants completed three self-report instruments outside VR through the dashboard. Positive and negative affect were measured with the 20-item Chinese version of the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988; Huang et al., 2003) on a 5-point scale, with participants rating how they felt at that moment. Scores are the sums of ten positive-affect (PA) and ten negative-affect (NA) items (range 10–50 for each). State anxiety was measured with the 20-item state subscale of the Chinese State–Trait Anxiety Inventory, Form Y (STAI-S; Spielberger et al., 1983; Li and Qian, 1995) on a 4-point scale; the ten reverse-keyed items were recoded before summation (range 20–80).

Perceived restorativeness was assessed with a 22-item, 7-point instrument that combined items adapted and translated from the Perceived Restorativeness Scale (PRS; Hartig et al., 1997) and Restoration Outcome Scale (ROS; Korpela et al., 2008) with author-added items. For this exploratory memorial-context adaptation, we organized the items into fatigue (3 items), haste (3), external attention (3), ROS-derived recovery (5), and PRS-derived restorativeness (8). Fatigue, haste, and external attention are negatively keyed; the first two sets include author-added fatigue and time-pressure items, and the five-part organization is not a validated factor structure of either source scale. Participants rated each item on the original 1–7 scale, and we computed the mean score for each subdimension. The author-defined restorativeness composite sums the positively keyed items and subtracts the negatively keyed items (Table 2). All 22 items, their subdimension assignments, and the scoring key are provided in the open data repository (see Data availability).

## 2.5. Experimental procedure

Participants were tested individually. Each session comprised six stages (Fig. 4). The first five took place in VR with continuous EEG recording; the sixth consisted of questionnaires administered outside VR through the operator dashboard. Throughout Stages 1–5, the operator monitored the session via the dashboard and provided verbal guidance as needed (Section 2.3).

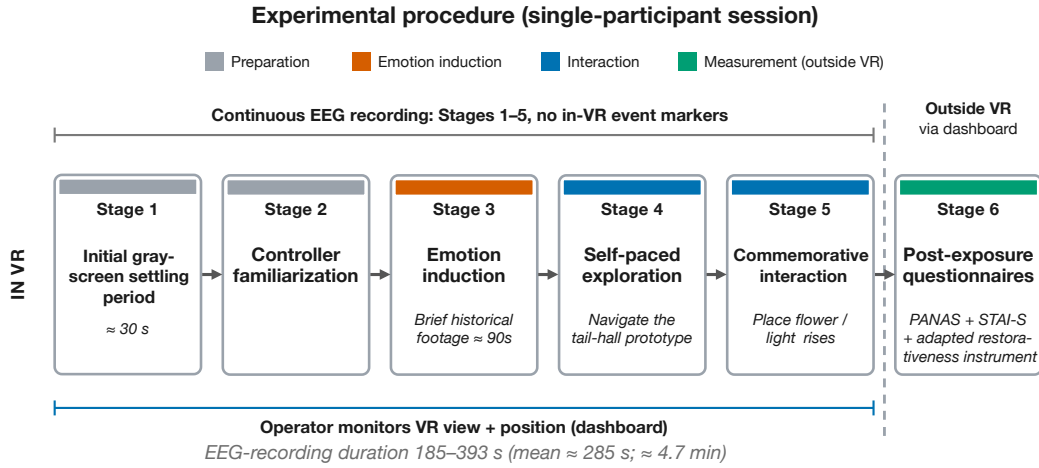


Figure 4: Six-stage session procedure. Stages 1–5 are conducted in immersive VR with continuous EEG recording; Stage 6 (post-exposure self-report) is administered outside VR via the dashboard.

Before equipment fitting, the operator verbally briefed each participant on informed consent (Section 2.1), the VR stages, controller use, and the ring-shaped affordance cues (Fig. 6). The participant was then seated and fitted with the EEG headband and HMD (Fig. 5). The operator checked electrode contact in the vendor software, which allowed recording only when all indicators were acceptable (“green”). EEG recording began with a 30-s settling period (Stage 1), during which participants remained still and viewed the same uniform gray display. This period could not be isolated reliably from the continuous recording; analyses therefore used whole-session indices without baseline correction. Participants then practiced navigation and interaction until comfortable (Stage 2; no fixed duration).

After exploring a simulated preceding exhibition hall, participants watched a single black-and-white segment assembled from publicly available historical footage of the Nanjing Massacre (approximately 90 s), presented on a wall-embedded screen following an in-VR prompt. This emotion-induction stage (Stage 3) was intended to approximate the affective context of the preceding exhibition. Participants then explored the assigned tail-hall at their own pace without directed tasks (Stage 4) and placed a virtual chrysanthemum at the cued installation (Stage 5), triggering the lamp-lighting response and the prototype-specific outcome display (Section 2.2). A spatialized bell from the far end of the exit corridor signaled completion and guided departure (Fig. 6).

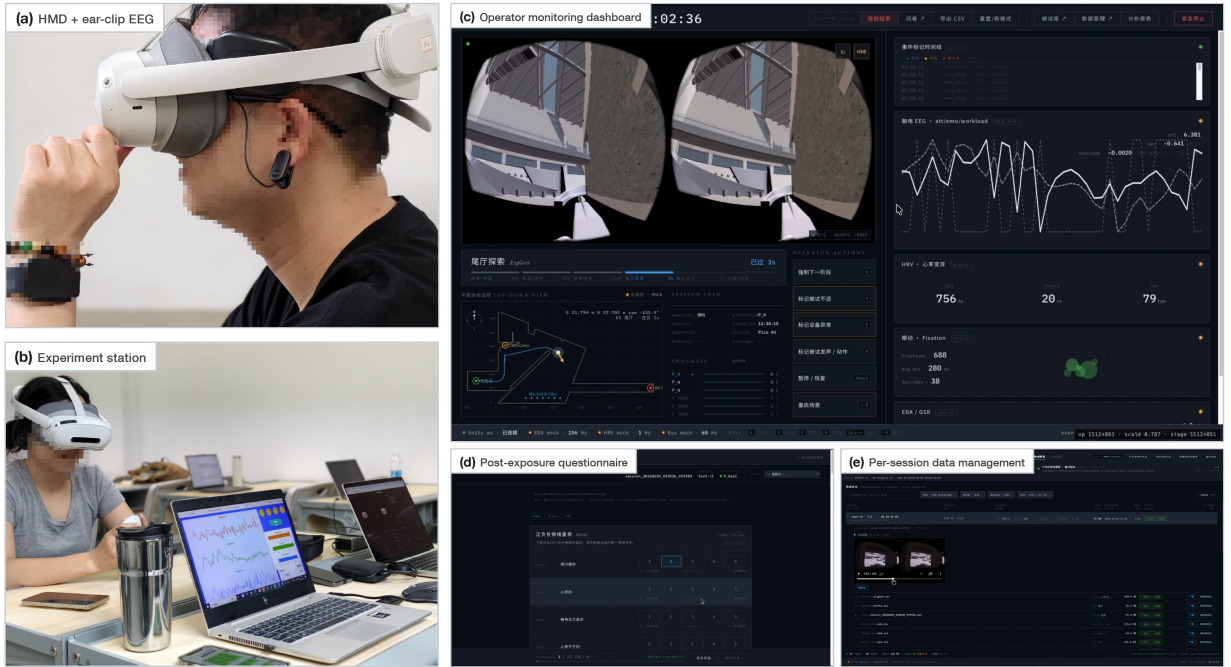


Figure 5: Experimental setup and operator dashboard. (a) Participant wearing VR headset and EEG headband. (b) Experimental station: EEG software (left) and dashboard (right). (c) Dashboard during operation, showing the VR mirror, floor-plan position trace, session controls, and an illustrative replay of EEG-derived records imported after offline analysis and linked to the corresponding participant and session record. EEG acquisition ran separately in the manufacturer's software. (d) Post-exposure questionnaire interface. (e) Per-session data management. Panels marked MOCK are inactive demonstration panels for planned modalities (Section 2.3).

The HMD and EEG headband were removed after Stage 5, and participants immediately completed the three questionnaires through the dashboard (Stage 6; Section 2.4.2). The operator then observed participants informally and remained available for questions. Post-session procedures did not include standardized debriefing or assessment with an adverse-event checklist or cybersickness instrument, and the informal observations were not recorded at the participant level. In-VR durations (Stages 1–5) varied across participants (Section 3.1).

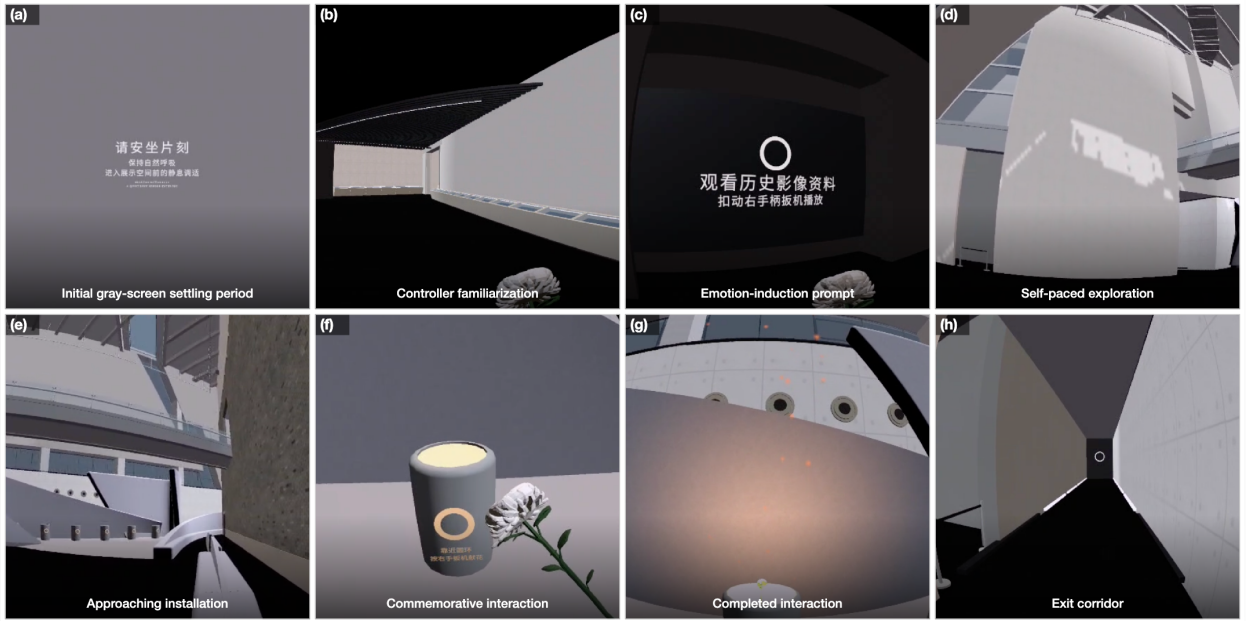


Figure 6: First-person VR views in chronological order. (a) Initial gray-screen settling period [“Please sit quietly for a moment; breathe naturally; take a resting pause before entering the exhibition space”]. (b) Controller familiarization; the participant holds a virtual chrysanthemum. (c) Emotion-induction prompt [“Watch the historical footage; pull the right trigger to play”]. (d) Self-paced exploration (Prototype 3 shown). (e) Approaching the interactive installation. (f) Commemorative interaction with a ring affordance cue [“Approach the lamp; pull the controller trigger to offer the flower”]. (g) Completed interaction: chrysanthemum placed and lamp lit. (h) Exit corridor with spatialized bell cue. Chinese-language interface text shown as delivered; English translations in brackets.

## 2.6. Data processing and statistical analysis

For each participant, we scored the self-report instruments as described in Section 2.4.2 and calculated the whole-session mean of each EEG-derived index for analysis. For each EEG-derived index, the open dataset also reports the standard deviation, median, minimum, and maximum. EEG-recording duration is defined as the length of the 1-Hz index record. It approximates the in-VR period from the start of Stage 1 through completion of Stage 5; dashboard trajectory logs were recorded separately. The open dataset uses participant codes P01–P12.

Given four participants per group, the analysis emphasizes the magnitude and direction of observed differences rather than null-hypothesis significance testing (Lee et al., 2014). We report bias-corrected standardized differences as Hedges’  $g$  (Hedges, 1981), with  $|g|$  values of approximately 0.2, 0.5, and 0.8 used as descriptive reference points for small, medium, and large differences (Cohen, 1988). Spearman rank correlations summarize cross-modal associations. Given the uncertainty of pilot estimates (Lakens, 2022), we used conventional effect-size scenarios for an a priori power analysis of a future three-group study. Statistical analyses were performed using Python 3.9.

## 3. Results

### 3.1. Protocol completion and data acquisition

All twelve participants completed the protocol without device failure. Questionnaire and EEG-index data were available for every participant. Figure 7 maps their movement trajectories onto the virtual tail-hall boundary. All participants reached the exit corridor after exploration and the commemorative task. Post-session observation was informal, so the incidence of adverse events and cybersickness was not formally assessed.

EEG-recording durations ranged from 185 to 393 s (mean  $\approx$  285 s, approximately 4.7 min). The whole-session EEG summaries cover the full VR sequence, including the common induction phase (Section 2.4.1). Operator guidance also varied: some participants needed more navigation assistance, particularly when searching for the interactive installation.

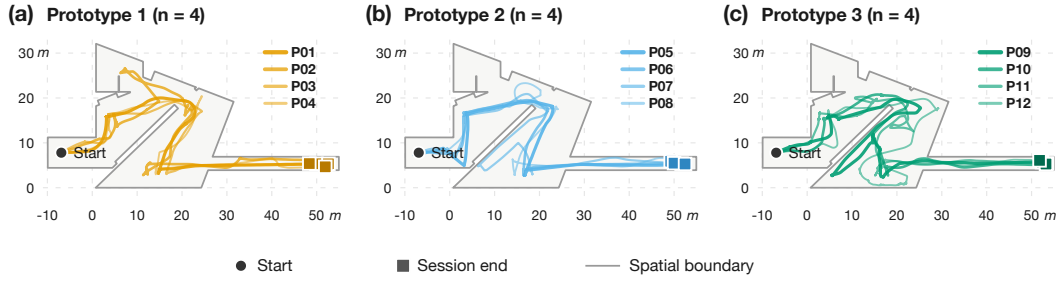


Figure 7: Controller-derived virtual movement trajectories for all twelve participants, overlaid on the spatial boundary and grouped by prototype. Every participant moved through the full virtual length of the space ( $\approx 55$  m).

### 3.2. Self-report profiles across prototypes

Table 2 reports group means and standard deviations. Figure 8 summarizes between-prototype differences as Hedges'  $g$ , with the full numerical matrix in Supplementary Table S1. Figure 9 shows individual scores and group means for six key measures.

**Table 2**

Descriptive statistics by prototype group ( $M \pm SD$ ).

| Measure                                             | Prototype 1 ( $n = 4$ ) | Prototype 2 ( $n = 4$ ) | Prototype 3 ( $n = 4$ ) |
|-----------------------------------------------------|-------------------------|-------------------------|-------------------------|
| EEG-recording duration (s)                          | 298 $\pm$ 56            | 260 $\pm$ 40            | 296 $\pm$ 90            |
| PANAS-PA (10–50)                                    | 29.5 $\pm$ 5.8          | 28.0 $\pm$ 10.2         | 34.0 $\pm$ 7.3          |
| PANAS-NA (10–50)                                    | 32.5 $\pm$ 9.8          | 16.8 $\pm$ 0.5          | 21.2 $\pm$ 5.3          |
| STAI-S (20–80)                                      | 51.2 $\pm$ 9.7          | 40.0 $\pm$ 11.6         | 40.8 $\pm$ 5.2          |
| Adapted-scale fatigue <sup>†</sup> (1–7)            | 3.75 $\pm$ 0.88         | 3.33 $\pm$ 1.12         | 2.67 $\pm$ 1.15         |
| Adapted-scale haste <sup>†</sup> (1–7)              | 4.00 $\pm$ 0.61         | 3.58 $\pm$ 1.00         | 3.25 $\pm$ 1.64         |
| Adapted-scale external attention <sup>†</sup> (1–7) | 3.42 $\pm$ 0.32         | 3.08 $\pm$ 1.87         | 2.58 $\pm$ 1.37         |
| ROS-derived recovery (1–7)                          | 4.05 $\pm$ 0.25         | 3.90 $\pm$ 0.90         | 4.25 $\pm$ 1.02         |
| PRS-derived restorativeness (1–7)                   | 4.44 $\pm$ 0.97         | 4.09 $\pm$ 1.16         | 4.81 $\pm$ 0.73         |
| Restorativeness composite <sup>‡</sup>              | 22.2 $\pm$ 3.3          | 22.2 $\pm$ 16.5         | 34.2 $\pm$ 21.9         |
| EEG attention                                       | 5.04 $\pm$ 2.15         | 3.16 $\pm$ 2.58         | 5.47 $\pm$ 1.74         |
| EEG emotion                                         | −0.52 $\pm$ 0.61        | 0.82 $\pm$ 1.19         | 1.32 $\pm$ 1.85         |
| EEG workload                                        | −0.001 $\pm$ 0.000      | −0.001 $\pm$ 0.001      | 0.000 $\pm$ 0.002       |

Note. PANAS = Positive and Negative Affect Schedule; STAI-S = State-Trait Anxiety Inventory, state subscale. Scores for the five author-defined item groups are reported as means across their respective items (range 1–7), with labels based on item content or source (Section 2.4.2). <sup>†</sup> Negatively keyed: lower scores indicate a more restorative response (raw means; scoring direction is accounted for in the composite). <sup>‡</sup> Composite = (recovery + restorativeness sums) – (fatigue + haste + external-attention sums); range −50 to +82. EEG indices are whole-session means of vendor-derived scores. Higher PANAS-NA and STAI-S scores indicate greater negative affect and state anxiety, respectively. The sign of  $g$  follows each measure's scoring direction.

Prototype 1 showed higher state anxiety than Prototypes 2 and 3 (STAI-S:  $g = 0.91$  and  $1.17$ , respectively). It also had higher negative affect; the estimate for Prototype 1 versus Prototype 2 was  $g = 1.96$ . Three of four Prototype 2 participants reported the same PANAS-NA score, resulting in very low within-group variance.

Prototype 3 had higher mean positive-affect and perceived-restorativeness scores than Prototype 2 (PANAS-PA:  $g = -0.59$ ; restorativeness composite:  $g = -0.54$ ; PRS-derived restorativeness:  $g = -0.65$ ). Negative affect was also higher ( $g = -1.05$ ), whereas state anxiety was similar ( $g = -0.07$ ). These contrasts describe the combined difference in interface geometry and displayed outcome (Section 2.2). For the restorativeness composite, the 12-point mean difference was smaller than the group standard deviations of 16.5 and 21.9.

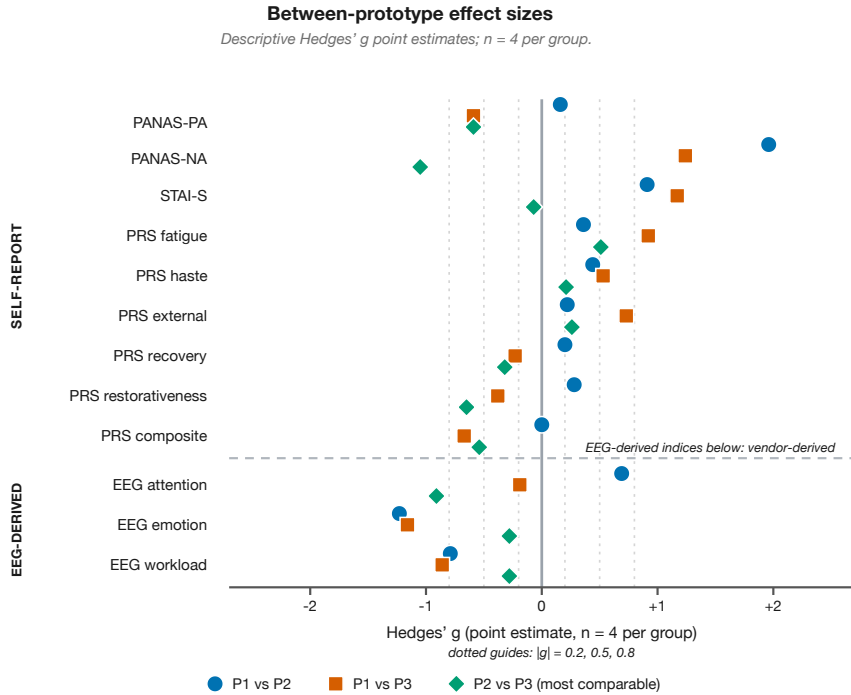


Figure 8: Between-prototype effect sizes (Hedges'  $g$ ) for self-report and EEG-derived measures. Each row shows three pairwise contrasts; the sign of each contrast reflects the first-named prototype's mean minus the second-named prototype's mean. Dotted reference lines mark  $|g| = 0.2, 0.5, 0.8$ . The six rows beginning with "PRS" are compact in-figure labels for adapted-scale fatigue, haste, external attention, ROS-derived recovery, PRS-derived restorativeness, and the author-defined restorativeness composite, respectively (Section 2.4.2).

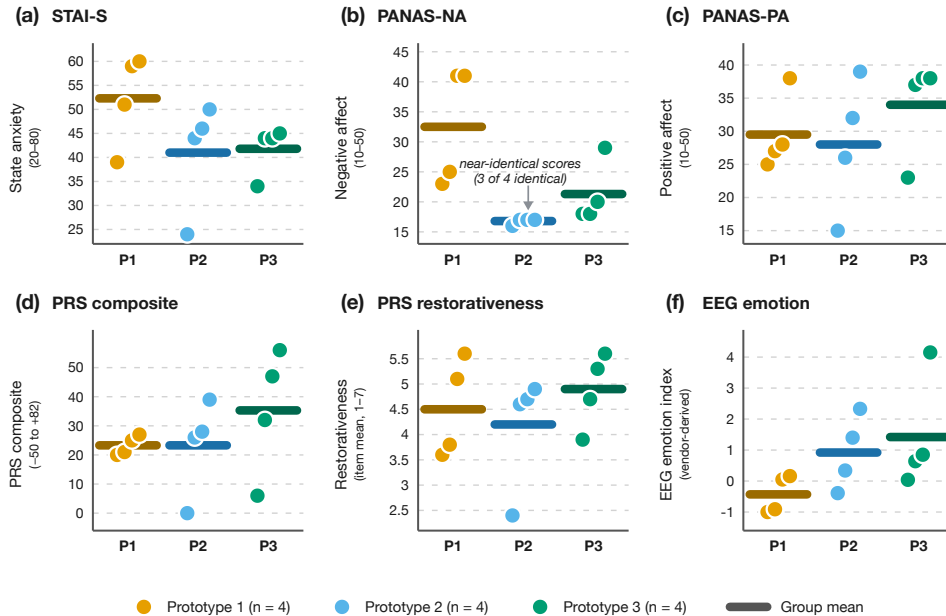


Figure 9: Individual participant scores (points) and group means (bars) for six key outcome measures, by prototype ( $n = 4$  per group). Panels (d) and (e) correspond to the author-defined restorativeness composite and PRS-derived restorativeness, respectively.

### 3.3. Whole-session EEG indices

Prototype 1 had a lower EEG emotion index than Prototypes 2 and 3 ( $g = -1.23$  and  $-1.16$ , respectively). The attention index was higher in Prototype 3 than in Prototype 2 ( $g = -0.91$  for Prototype 2 vs. 3). The vendor-derived indices are reported on their original scales; attention is interpreted separately from perceived restorativeness. Workload showed little dispersion, particularly in Prototype 1, where its standard deviation rounded to zero (Table 2). Workload is tabulated for descriptive completeness; interpretation focuses on the attention and emotion indices.

Supplementary Fig. S1 provides a standardized overview of the self-report and EEG-index profiles using the same observations.

### 3.4. Exploratory cross-modal associations

Table 3 reports all fifteen Spearman rank correlations between the five self-report scores and three EEG-derived indices across the twelve participants. The restorativeness composite–EEG emotion correlation was  $r = +0.50$ , with an approximate 95% confidence interval of  $-0.1$  to  $+0.8$ .

As a sensitivity check, we examined associations between EEG-recording duration and the measures listed in Table 3. Associations between duration and the five self-report scores were weak ( $|r| \leq 0.32$ ), while the association with the EEG emotion index was  $r = -0.50$ . Because duration covers the complete VR sequence (Section 2.6), these associations describe variation across whole recordings.

**Table 3**

Cross-modal Spearman rank correlations between self-report and EEG-derived measures ( $n = 12$ ).

| Self-report                 | EEG attention | EEG emotion | EEG workload |
|-----------------------------|---------------|-------------|--------------|
| PANAS-PA                    | −0.02         | −0.18       | +0.29        |
| PANAS-NA                    | +0.17         | −0.36       | −0.02        |
| STAI-S                      | −0.08         | −0.06       | −0.58        |
| PRS-derived restorativeness | −0.22         | +0.20       | +0.40        |
| Restorativeness composite   | −0.06         | +0.50       | +0.28        |

*Note.* Spearman's  $r$  across all twelve participants. Values are descriptive. Interpretation of workload associations is limited by the index's near-invariance and uncertain construct validity (Sections 2.4.1 and 3.3).

### 3.5. Sample-size planning scenarios

We conducted an a priori power analysis for a future single-factor, three-group study using one-way analysis of variance (ANOVA) ( $\alpha = .05$ ; 80% power). Required sample sizes were calculated from the noncentral  $F$  distribution using the accompanying open analysis script. Although observed  $\eta^2$  values reached medium-to-large benchmarks, the bias-corrected  $\omega^2$  estimates were negative for the restorativeness composite and PRS-derived restorativeness and positive for STAI-S and the EEG emotion index.

Given this uncertainty in the pilot estimates, we used conventional effect-size scenarios for sample-size planning. Under these scenarios (Cohen, 1988), a medium effect (Cohen's  $f = 0.25$ ) requires approximately 53 participants per group, and a large effect ( $f = 0.40$ ) approximately 22. These scenarios yield a planning range of approximately 22–53 participants per group for the specified three-group design. The final recruitment target should be based on the prespecified primary outcome and target effect size, with an allowance for attrition and unusable physiological data. Alternative designs require a separate power calculation.

## 4. Discussion

### 4.1. Operational feasibility for early-stage design evaluation

The pilot demonstrated the laboratory feasibility of combining self-paced seated exploration, a commemorative task, wearable EEG recording, and post-exposure questionnaires. Building on multimodal VR approaches to architectural evaluation (Pei et al., 2023; Li et al., 2023; Tashiro and Harada, 2025), the protocol combined historical content, spatial exploration, and commemorative participation in a single VR sequence. Session completion and participant-level data collection provide a practical basis for obtaining experiential feedback before a design is implemented. For design evaluation, this means considering how participants explore and use a space alongside its visual qualities. The implementation identified phase-linked recording and consistent operator guidance as priorities for larger comparisons.

During exploration, participants could choose when to move, pause, and redirect their view within a shared sequence and task structure. Controller-based navigation made this possible while participants remained seated. A comparison with matched passive viewing could clarify how self-paced exploration and commemorative interaction influence presence, usability, and affective responses.

#### 4.2. Perceived restorativeness in a memorial context

Research on memorial design examines how spatial features support visitors' exploration, commemoration, and interpretation of the past (Wagoner and Brescó, 2022). Work on affective curatorship similarly considers the interplay of exhibition themes, spatial design, and visitor activities (Varutti, 2023). Applied to the tail-hall, these perspectives suggest that design evaluation should address reflection and commemoration as well as visitors' emotional needs at the end of the exhibition. Pleasantness alone is therefore an insufficient criterion for evaluating its design.

We assessed perceived restorativeness alongside positive and negative affect and state anxiety to describe participants' experiences at the end of the memorial sequence. Prototype 3 had higher mean perceived-restorativeness and positive-affect scores than Prototype 2, alongside higher negative affect. The coexistence of these responses in this sample supports considering perceived restorativeness alongside both positive and negative affect when evaluating tail-hall designs. Perceived restorativeness thus contributes one dimension to the assessment of memorial experience; evaluating the emotional transition itself requires measurements at multiple points in the visit.

#### 4.3. Prototype comparisons and design implications

Differences between the prototype profiles raise two sets of questions for architectural evaluation. For Prototypes 2 and 3, the roles of interface geometry and outcome display (individual versus preconfigured collective) need to be distinguished, as both attributes varied together in this pilot. This comparison highlights commemorative outcome display as a design attribute to consider alongside geometry. Prototype 1 showed another profile: higher anxiety and a lower whole-session EEG emotion index accompanied a combination of enclosure of the commemorative interaction area, timber finish, an overhead plane, and reduced scene brightness. Evaluating this configuration requires attention to both enclosure and lighting, with geometry, finish, and illumination varied separately to identify responses associated with each design adjustment. These observations identify concrete comparisons for prototype refinement: interface geometry and commemorative outcome display, and configurations of enclosure, overhead plane, and lighting.

Comparing these design configurations also requires an understanding of how the selected measures relate to one another. The restorativeness composite was positively associated with the vendor-derived EEG emotion index (Spearman's  $r = 0.50$ ). The estimate has a wide confidence interval and emerged from fifteen exploratory correlations, so replication with interpretable physiological measures is a priority. Phase-linked physiological records would separate responses during the tail-hall experience from those during the preceding induction, helping to clarify when the association occurs.

#### 4.4. Limitations and future research

The EEG results summarize proprietary indices over the entire recording, combining the common induction with prototype exploration and interaction. Linking responses to participants' differing paths is a recognized difficulty in freely navigated VR (Hu and Roberts, 2020). Shared timestamps, event markers, and stage-level duration records are therefore important for relating physiology to the experience as it unfolds. Access to raw EEG and transparent signal processing would also allow artifact handling and physiological interpretation to be assessed.

Procedural control can be strengthened while retaining self-paced exploration. The common induction, viewing position, instructions, and operator cues can be standardized; exploration duration can be recorded separately from total session duration and included explicitly in the analysis. Scene photometry is another priority: luminance and illuminance were not measured, and Prototype 1's overhead plane also reduced environmental illumination. Attribute-specific comparisons need to distinguish the geometric condition from its accompanying lighting differences.

The small convenience sample and allocation by the operator limit the precision of between-prototype estimates and their generalizability to museum visitors. A larger, more diverse sample and a recorded allocation procedure are needed for comparative evaluation. Recording prior VR or gaming experience and using validated screening for cybersickness susceptibility and trauma sensitivity would strengthen participant characterization. Transfer to on-site evaluation also requires consideration of the virtual setting: real-virtual comparisons indicate that correspondence with on-site responses depends on the measure being considered (Lu and Lau, 2025).

The adapted restorativeness instrument and its author-defined composite require evaluation of their factor structure and construct validity in the memorial context. Post-exposure ratings capture end-of-session differences between participants; additional pre-exposure and post-induction assessments are needed to distinguish initial differences from changes during the sequence.

## 5. Conclusion

An operator-supported VR protocol combining self-paced seated navigation, a commemorative task, and multi-modal data collection was feasible in this laboratory pilot. All twelve participants completed the procedure and provided questionnaire and EEG-index data.

Exploratory comparisons described response profiles across the three design configurations. Prototype 1 showed higher state anxiety and a lower EEG emotion index than Prototypes 2 and 3. Prototype 3 had higher mean positive-affect and perceived-restorativeness scores than Prototype 2, alongside higher negative affect. These profiles highlight the importance of assessing perceived restorativeness alongside positive and negative affect in memorial spaces. The association between the restorativeness composite and the EEG emotion index offers a specific relationship to examine in subsequent measurement studies.

For architectural design evaluation, future comparisons should address interface geometry and commemorative outcome display, as well as the combination of enclosure, overhead plane, and lighting. Larger studies can examine these attributes separately, with phase-linked physiological recording and consistent operator guidance. The present protocol provides a practical basis for incorporating spatial exploration, commemorative participation, and multimodal assessment into the early-stage evaluation of memorial interiors.

## Declarations

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**CRedit authorship contribution statement** Shaoqian Wang: Conceptualization, Methodology, Software, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization. Jing Huang: Validation, Writing – review & editing. Chao Wang: Investigation, Methodology, Validation. Andong Lu: Supervision, Methodology, Writing – review & editing, Project administration.

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**Data availability** De-identified participant-level questionnaire responses, per-second vendor-derived EEG indices, the adapted restorativeness instrument and scoring key, and the analysis script are openly available at <https://doi.org/10.5281/zenodo.20814511> (Wang et al., 2026). The VR application is not distributed because its third-party historical footage is not licensed for redistribution within the software package. The dashboard source code remains non-public as research infrastructure under active development.

**Declaration of AI use** Claude (Anthropic; Opus 4.6) and Codex (OpenAI; GPT-6) were used for translation and language editing; Codex also assisted with analysis-code development. The authors verified the translation (checked by Shaoqian Wang), reviewed the manuscript and analysis code, confirmed the accuracy and originality of the content, and checked that the tools' terms of use permit their use for this publication. All authors take full responsibility for the entire manuscript, including the accuracy of its references.

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