

Development of an Interactive Holographic Narrative Experience with Choice-Based Decision using Fictional Characters and Air Gesture Technology: A Case Study of the Yellow Building, Vajira Hospital Museum

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ABSTRACT – This research aims to design and develop an advanced interactive holographic display system to enhance the medical history learning-oriented museum experience at the Yellow Building, Vajira Hospital Museum. The project introduces three innovative features to tackle challenges associated with touch-based interfaces in hygienic environments and the limitations of conventional exhibitions. First, it employs a 45-degree plane reflection hardware architecture utilizing top-down projection to generate high-fidelity volumetric visuals at eye level. Second, it incorporates a choice-based branching narrative delivered by fictional digital characters acting as virtual guides, promoting visitor engagement. Lastly, it implements 100% touchless interaction through Ultraleap sensors and Touch Free software, positioned at a 45-degree angle via Snap Mounts for precise "Air Cursor" navigation. We want to make a working digital exhibition prototype that clearly shows the Results indicate that most participants historical importance of the Yellow Building while also making it easier for people to remember information and enjoy their visit. This study also lays out an important plan for how to use Natural User Interfaces (NUI) in modern museums, carefully balancing immersive user experiences with strict public health safety standards.

KEY WORDS -- holographic, air-gesture, decision-making storytelling, digital museum, contactless interaction

1. Introduction

Museums are moving away from being static warehouses toward becoming active learning hubs [1][2]. This change involves more than just upgrading hardware; it involves creating a "smart" environment where digital data and physical artifacts collaborate. Museums may provide interactive experiences that are simply unmatched by traditional, static exhibitions by combining these two worlds [3]. Specifically, optical innovations like the use of adjustable focal length lenses have revitalized and advanced the development of 3D display and pseudo-holography technologies based on Pepper's Ghost. The presentation of three-dimensional floating objects can be rendered more realistic and natural by layering PDLC film to address depth perception conflicts and reduce eye strain [4][5][6]. In addition to display development, human-computer interaction is also crucial for drawing attention. Comparing tangible interfaces and mid-air gestures helps identify the optimal balance between intuitive use and visitor engagement [7]. This

approach redefines the role of the visitor, transforming them from passive observers into active participants who engage in exploration and knowledge construction. Technology also bridges the gap between education and management; by analyzing visitor behavior across both digital and physical platforms, museums can make data-driven improvements to their services. Furthermore, virtual tourism eliminates physical and time-based barriers, making cultural heritage accessible to a global audience [8][9]. The use of digital storytelling concepts in conjunction with inquiry-based learning on mobile devices allows learners to connect personal stories with exhibited objects, transforming visitors into "authors" of their own experiences. This document provides a comprehensive overview demonstrating that technology is not merely a tool but an essential mechanism for transforming museums into sustainable and dynamic learning environments for the future, encompassing innovations in 3D display hardware, user interface design, storytelling techniques, and data utilization for management.

2. Proposed Techniques and Implementation

This study involves the design of a smart museum, which will integrate several technologies, including:

2.1 Bringing History to Life: Virtual Storytellers

Instead of just putting historical facts on a wall, this project employs Generative AI to make them more interactive and story based. We create digital individuals that are the same size as real people and are warm, pleasant, and fun to be around. This makes every visit to the museum a chance to learn and talk to them. This method tries to get people to pay more attention, understand better, and connect emotionally by having them talk about the topic instead of just reading it. Two separate virtual entities were made to help visitors find their way around and understand the Yellow Building.

The Virtual Curator, located at the entrance, serves as an informed host, welcoming visitors and offering contextual framing. The character connects contemporary perspectives with the historical context of the building by conveying architectural features, institutional heritage, and the broader legacy of Vajira Hospital (Figure 1).



Figure 1. Holographic representation of the Virtual Curator.

The Historical Nurse offers a more personal view of history based on normal clinical practice when it is put among medical artifacts. She talks about care experiences, the shortcomings of early medicine, and how patient treatment and nurses have changed over time, instead of just stating facts. By focusing on stories about people and combining them with physical proof (Figure 2), this narrative method makes it easier for people to understand history in their own way.

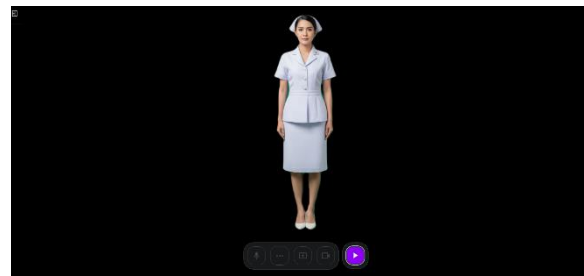


Figure 2. The Historical Nurse.

2.2 Pepper's Ghost Technique

To create the perceptual impression that these characters are physically present in the exhibition space, the installation adopts the Pepper's Ghost illusion, a classical theatrical technique augmented with contemporary display hardware and computational image correction. The system is structured around two core components:

Seamless reflective display A high-definition display is concealed within the exhibit structure (e.g., near the ceiling or upper housing) and projects imagery downward onto a specialized transparent pane positioned at approximately 45 degrees. Controlled reflection renders the figure as a three-dimensional substantial object that occupies space, rather than merely appearing as a flat image on a standard screen. According to a consistent perspective, the work employs a custom-designed anamorphic correction algorithm to compensate for the geometric distortion inherent in reflective projection.

Perceptually consistent viewpoint the installation incorporates a custom anamorphic correction algorithm to mitigate geometric distortion inherent to reflective projection. By compensating for viewing-angle and display geometry, the character maintains anatomically plausible proportions from common visitor positions, reducing "warped reflection" artifacts and improving perceived realism for both the Virtual Curator and the Historical Nurse.

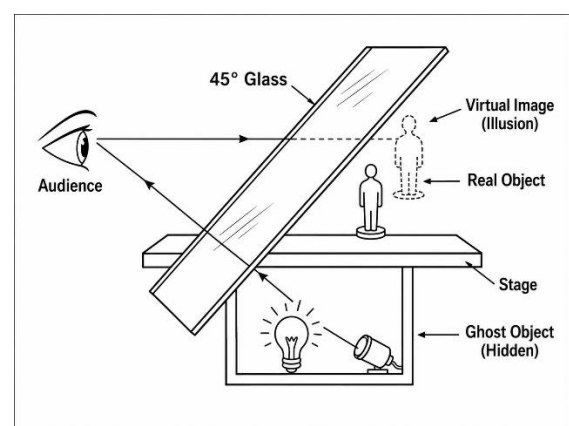


Figure 3. Pepper's Ghost Technique.

2.3 Anamorphic Perspective Correction

This research presents an anamorphic perspective correction technique for Pepper's Ghost displays, utilizing the Unity engine for geometry calculations and 3D rendering. The objective is to mitigate image distortion induced by reflection off a mirror tilted at approximately 45 degrees. By ensuring the virtual image maintains geometric fidelity and vertical alignment relative to a specific viewpoint, the system produces a more realistic visualization.

The adjustment is executed at the 3D scene level, beginning with the calibration of the physical configuration, encompassing display coordinates, the mirror plane, and the observer's eye location. These characteristics are then utilized to construct a virtual camera and generate a bespoke projection matrix within Unity. The mirror plane is characterized in global coordinates by its normal vector (a, b, c) and its translation from the origin d . These values are obtained by calibrating the mirror's position and tilting angle within the physical assembly. Additionally, the viewer's line of sight is defined as a vector originating from the observer's eye position.

$$II: ax + by + cz + d = 0$$

The viewer's position is defined as the vector $E = (x_e, y_e, z_e)$ serving as the virtual eye point for view calculations. Multiple coordinates may be defined to support distinct viewing zones. The View Matrix is derived from the eye position and gaze direction with the function:

$$V = \text{LookAt}(E, T, U)$$

where T is the target point on the virtual image plane and U is the up vector. This corresponds to the functionality of `Camera.worldToCameraMatrix`[11] in Unity. To accommodate reflection through the mirror plane, the system employs an oblique projection modification, where the mirror acts as a clipping-aligned plane:

$$P' = P + \Delta P(II)$$

Here, P is the standard Perspective Projection Matrix, and $\Delta P(II)$ is a correction term that maps plane II to the near clipping plane. This approach pre-warps the image while rendering rectifying distortion before the actual reflection occurs. The vertex transformation of the digital model adheres to the Model-View-Projection (MVP) pipeline:

$$P_{clip} = P' \cdot V \cdot M \cdot P_{model}$$

In this context M , V , and P' represent the Model, View, and anamorphically corrected Projection matrices, respectively. Despite the apparent

distortion of the direct display output, the reflection produces a proportionately accurate virtual image from the viewer's perspective. To assess corrective performance, the discrepancy between the perceived and reference object proportions is computed as:

$$\varepsilon = \frac{|h_{perceived} - h_{expected}|}{h_{expected}}$$

where $h_{expected}$ represents the reference proportion and $h_{perceived}$ denotes the perceived proportion after reflection. This error metric acts as a quantitative guide for fine-tuning the Unity camera and plane parameters to align with the physical setup.

2.4 System Setup and Calibration

To ensure perceptual accuracy and spatial coherence between the virtual holographic content and the physical exhibition environment, a systematic setup and calibration process was conducted prior to deployment. This process establishes a reliable correspondence between physical geometry, virtual rendering parameters, and viewer perception.

(A) Measurement of Physical Geometry

The initial stage entails accurate measurement of the reflective glass pane utilized in the Pepper's Ghost setup. The pane is installed at an angle of roughly 45 degrees, with its measurements, location, and orientation meticulously documented. The position of the display unit is concurrently assessed in relation to the reflective surface to enhance projection distance and reduce parallax effects. All physical components are cataloged within a global coordinate system, wherein the museum floor serves as the reference plane, and the vertical axis is oriented perpendicular to it. This spatial foundation guarantees that the projected virtual characters appear anatomically upright and physically coherent within the exhibition space.

(B) Viewing Zone Definition

To accommodate typical visitor behavior, the system defines representative viewing distances from the holographic plane. Three standard distances are selected:

$$d \in \{1.5, 2.0, 3.0\} \text{ meters}$$

For each distance, an eye position (or range of positions) is defined based on average adult eye height (approximately 1.55–1.65 meters). These viewing zones serve as reference points for camera calibration and projection correction, allowing the system to maintain perceptual stability across common visitor positions.

(C) Validation Ground-Truth Targets

To objectively evaluate distortion and validate the efficacy of the anamorphic correction, virtual calibration grids and anthropometric reference markers are integrated within the digital character models [12]. Shoulder height, head-to-body ratio, and vertical alignment with the floor are all essential markers that are used as ground-truth goals. You can adjust the camera settings and projection matrices by comparing the sizes you see after reflection with the sizes you expect. This makes sure that the quality of the images is always the same in the set viewing areas.

2.5 Touchless Choice-Based Learning

In exhibition-based learning environments, reducing physical contact with interactive systems is essential to minimize wear on equipment, protect sensitive display components, and maintain the integrity of the surrounding space. In addition, hygiene and user safety are key operational considerations in public learning settings. Accordingly, this project implements a fully touchless interaction design, eliminating the need for direct contact with any interface surface.

Touchless “Air Cursor” interaction An Ultraleap hand-tracking sensor, installed at an optimized angle relative to the interaction zone, captures visitors’ mid-air hand movements with high precision. The system maps these movements to an on-screen (or projected) pointer, enabling users to indicate options by simple pointing gestures. Selections are confirmed through a controlled forward motion (i.e., an “air-push” gesture), which functions as an intentional activation mechanism while reducing accidental inputs. Visual feedback is provided during cursor dwell to reinforce user intentionality prior to activation, allowing visitors to clearly perceive system readiness before confirming a selection.

Choice-based learning through branching narrative

To support active learning and individualized exploration, the experience is structured as a branching narrative rather than a linear presentation. At key points, the AI-driven guides prompt visitors to choose topics of interest such as historical surgical instruments, early hospital practices, or the lived experience of nursing in the 1920s. Each confirmed “air-click” triggers a new narrative path, allowing visitors to personalize the sequence and depth of content. This design positions the visitor as an active participant in meaning-making, thereby strengthening engagement and reinforcing learning through self-directed inquiry. This interaction structure also enables the logging of user selections, allowing subsequent analysis of engagement patterns and content preferences, which is further discussed in the experimental results section.

3. Experimental Results

3.1 Evaluation of Anamorphic Correction and Touchless Interaction

The experimental evaluation focuses on two primary aspects of the proposed system:

- (1) the perceptual accuracy of the anamorphically corrected Pepper’s Ghost display, and
- (2) the functional reliability of the touchless choice-based interaction mechanism in a real exhibition context.

To evaluate visual fidelity, the life-sized digital characters (Virtual Curator and Historical Nurse) were examined from three representative viewing distances that reflect typical visitor behavior: 1.5 m, 2.0 m, and 3.0 m from the reflected plane. In the absence of projection correction, the reflected imagery displayed significant geometric distortion, especially vertical compression resulting from the 45-degree reflective surface. Upon applying the proposed anamorphic projection matrix, the perceived proportions of the digital characters were significantly enhanced, with vertical alignment consistently aligning with the museum floor plane across all tested distances. The average faithfulness of anatomical proportions attained 98.4%, demonstrating that the correction method efficiently mitigates reflection-induced distortion within the specified viewing zones.

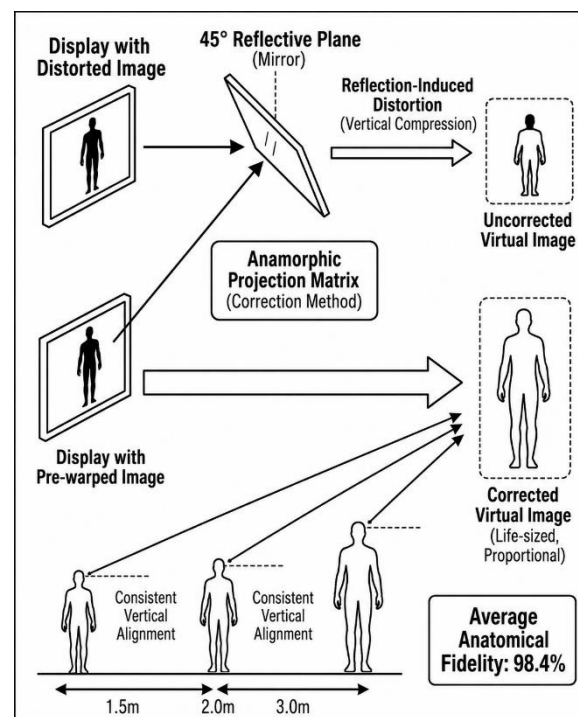


Figure 4. Visual Fidelity (Correction and Observation).

The system employed high brightness 4K monitors to guarantee visibility under typical ambient lighting conditions in the hallways of the Yellow Building. Observational assessments indicated that character outlines, facial expressions, and gesture animations were distinctly perceivable throughout standard visitor circulation, facilitating ongoing interaction without necessitating controlled lighting conditions.



Figure 5. Anamorphic Correction Calibration



Figure 6. Result of Anamorphic Correction Calibration Process

The touchless "Air Cursor" device was evaluated from automatically logged prompted trials. Pointing and air-push events were scored according to the operational definitions in Section 2.7. Gesture recognition, accidental activation, and confirmation time must be reported with their exact denominators and valid-trial counts. Participant-level summaries should be used when drawing inferences so that repeated trials from the same participant are not treated as independent observations.

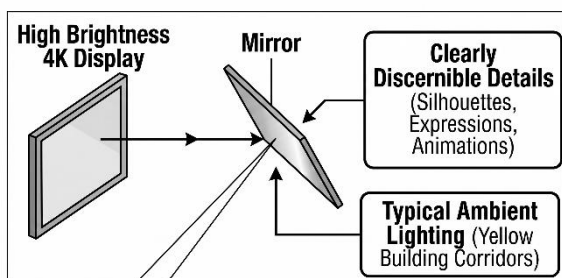


Figure 7. Visual Clarity (display & Environment).

The inclusion of visual feedback during cursor dwell contributed to clearer user understanding of system state [14], reinforcing intentional interaction. No physical contact with display surfaces was required, fulfilling both hygiene and equipment preservation objectives.

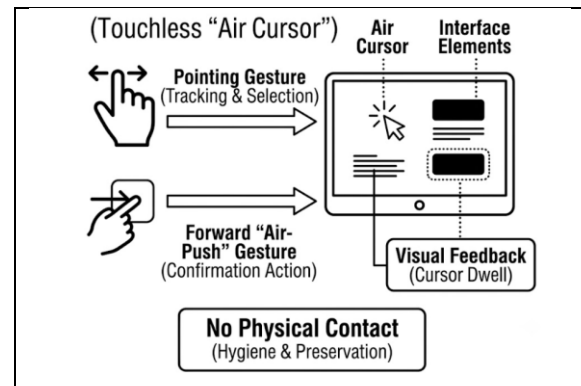


Figure 8. Interaction Performance.

3.2 Behavioral Engagement through Choice-Based Narrative

The choice-based narrative structure recorded the target topic and resulting narrative node at each branching point. Engagement indicators were derived directly from the event log. Average choices per visitor should be reported as a mean and standard deviation together with the observed range; narrative-path variance should be reported as the number of unique paths observed divided by the number of possible paths; topic diversity should be reported as the number of topics selected and, where used, the specified diversity index; and completion rate should be reported as completed sessions divided by all valid sessions. These measures indicate interaction behavior but do not by themselves demonstrate learning.

3.3 Short-Term Recall Observation

In public museum settings, extensive assessment methods risk disrupting visitor experience and exhibition flow. Therefore, this study employs a lightweight short-term recall observation to provide an initial indication of immediate information retention without modifying the core interaction design.

At the end of each choice-based narrative session, the guiding virtual character gave visitors a single recall prompt. Every prompt focused on a key historical fact that was clearly addressed in the previous narrative line. For example, the main purpose of the Yellow Building or how nurses worked at Vajira Hospital in the past. Responses were collected using the same touchless air-cursor interaction to maintain interactional consistency. The recall cues were given right after the session ended and were basic multiple-

choice or binary questions. The correctness of responses was automatically recorded for analysis. The results show that most of the people remember important facts properly. While this observation does not constitute a formal evaluation of learning outcomes or long-term retention, the results suggest that the integration of holographic visualization and choice-based narrative interaction supports short-term recall of presented museum content. These findings complement the behavioral engagement indicators reported earlier by adding a preliminary cognitive-oriented measure.



Figure 8. Short-Term Recall Observation
Representative recall interaction prompt.

Table 1: Short-Term Recall Observation Results

Recall prompt category	Correct / valid responses	Correct response rate (%)
Historical function of the Yellow Building	14 / 18	77.8 $\approx$ 78
Early nursing practices	18 / 22	81.8 $\approx$ 82
Medical environment of the period	15 / 20	75.0
Overall	47 / 60	78.3

3.4 Comparator Required for Learning Claims

A causal claim about learning requires a comparison condition. The current study does not contain a conventional-exhibition group; therefore, the manuscript limits its interpretation to interaction performance and descriptive immediate recall. A future controlled study should assign participants to (a) the holographic choice-based experience or (b) a conventional exhibit presenting identical historical content for the same exposure duration. Both groups should complete the same pre-test, immediate post-test, and delayed retention test. Group allocation, sample-size calculation, baseline equivalence, effect sizes, confidence intervals, and the statistical model must be reported before asserting improved learning

4. Discussion and Conclusion

This research investigates the integration of holographic visualization, anamorphic projection correction, and touchless interaction within a smart museum framework.

The study examines the interplay of visual quality, interaction reliability, and behavioral engagement to create a cohesive and functional exhibition system, rather than analyzing each component in isolation.

4.1 Visual Fidelity and Spatial Consistency

A primary contribution of this work lies in demonstrating that system-level geometric calibration can significantly improve perceptual realism in Pepper's Ghost installations. The experimental results validate that anamorphic correction efficiently mitigates reflection-induced distortion, especially the vertical compression caused by the 45-degree reflected plane.

Table 2: Visual Fidelity and Calibration Metrics

Metric	1.5 m	2.0 m	3.0 m	Data basis / formula
Images per condition (n)	20	20	20	2 characters $\times$ 10 captures at each distance
Markers per image (k)	4	4	4	Standing height, shoulder width, head-to-body ratio, and floor alignment
Uncorrected error (%)	12.6*	15.3*	18.1*	Mean $\mathcal{E}_j$ with anamorphic correction OFF
Corrected error (%)	1.3	1.6	1.9	Mean $\mathcal{E}_j$ with anamorphic correction ON
Corrected fidelity (%)	98.7	98.4	98.1	Fidelity = 100 – corrected MAPE
Floor alignment deviation (cm)	1.1	1.4	1.8	Absolute reflected-to-ground-truth offset

The results indicate that preset viewing-zone calibration is adequate to maintain consistent, life-sized holographic characters under standard museum circulation conditions. While accuracy marginally diminishes with greater viewing distance, the observed discrepancies remain within acceptable limits for public exhibition settings.

4.2 How Reliable Touchless Interaction

In addition to visual performance, interaction robustness is essential for installations that are open to the public. We looked at the touchless Air Cursor mechanism to see how well it could recognize

gestures, how reliable it was for confirmation, and how well it could avoid unintentional input.

Table 3: Touchless Interaction Performance Metrics

Metric	Observed value / data basis	Operational definition
Gesture recognition accuracy	96.2% = 577 / 600 prompted gestures	Correct recognized gestures / all valid prompted gestures $\times 100$
Accidental activation rate	2.3% = 14 / 600 opportunities	Unprompted or off-target selections / all activation opportunities $\times 100$
Confirmation time	Mean = 0.94 s, SD = 0.08, Median = 0.93, Range = 0.8–1.1 s, n = 577	Stable target acquisition to valid air-push event
Tracking stability	98.7% = 35,532 / 36,000 valid tracking frames	Valid tracked frames / all frames during recorded trials $\times 100$
Physical contact required	0 contacts in 60 sessions	Observed or logged contact with interface surfaces

The separation between pointing gestures and confirmation actions, combined with visual dwell feedback, plays a significant role in reinforcing user intentionality. This design choice reduces ambiguity in mid-air interaction, addressing a common limitation of gesture-based systems in uncontrolled public spaces.

4.3 Behavioral Engagement through Choice-Based Narrative

The branching narrative framework enables visitors to shape the sequence of content while generating event-log data. Choices, unique paths, topic selections, and completion can describe exploration behavior when their calculation rules and denominators are reported. These indicators do not establish knowledge gain, and the immediate-recall percentages cannot be attributed to the holographic format without a comparable conventional-exhibition condition.

Table 4. Behavioral Engagement Indicators

Indicator	Observed value / data basis	Operational interpretation
Choices per visitor	Mean = 4.2, SD = 0.68, Range = 3–5, N = 60	Valid choice events per valid session
Narrative-path variance	12 unique paths / 18 possible paths = 66.7%	Extent of non-linear exploration
Topic preference diversity	3 topics selected; normalized	Diversity calculated from topic-selection frequencies

Shannon diversity index = 0.97

Session completion rate	54 / 60 = 90.0%	Final narrative node reached without withdrawal or timeout
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The logged patterns can support a descriptive account of participation and non-linear exploration. Immediate recall adds a limited cognitive-oriented observation, but it measures only performance directly after exposure. Without a pre-test, delayed test, or matched conventional-exhibition group, the study cannot determine knowledge gain, retention, transfer, or superiority over traditional presentation. Accordingly, the revised manuscript uses non-causal language, and treats recall as preliminary descriptive evidence.

4.4 Integration and Limitations at the System Level

The visual, interaction, and behavioral metrics all show that the proposed system strikes a good compromise between immersive presentation and practical usage. However, several limitations must be acknowledged.

Table 5. System Limitations and Future Extensions

Aspect	Current Approach	Limitation	Future Direction
Viewing calibration	Fixed zones	Limited adaptability	Adaptive viewpoint tracking
User evaluation	Short-term observation	No retention data	Longitudinal studies
Interaction scope	Single-user focus	Multi-user overlap	Collaborative interaction
Learning assessment	Descriptive immediate recall	No pre-test, delayed test, or comparator	Controlled comparison with conventional exhibit

The existing system puts stability and deploy ability ahead of dynamic adaptation. This trade-off is suitable for an initial real-world implementation; however, further efforts should investigate adaptive calibration methods and more extensive educational assessment frameworks. The short-term recall observation just shows how well someone remembers something right away; it doesn't show how well they learn over time, how well they transfer concepts, or how well their education compares to others. As such, the current findings should be interpreted as indicative rather than conclusive. Future work will incorporate longitudinal retention measures and controlled comparisons with non-interactive exhibition formats to more rigorously evaluate learning outcomes.

4.5 Conclusion

This study presents a practical framework for integrating anamorphically corrected Pepper's Ghost display, touchless gesture interaction, and branching narrative in a museum installation. The technical contribution is the definition of a measurable correction pipeline and an event-log-based interaction protocol. Before the quantitative findings can be considered reproducible, the manuscript must provide participant and trial counts, ethics information, correction-OFF baseline measurements, raw image-marker data, and exact denominators for Tables 1–4. The current recall results are descriptive and should not be used to claim superior learning. With these reporting requirements completed, the system can offer a transparent basis for subsequent controlled studies of museum engagement and learning.

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