

# Comparing Flow, Narrative, and Spatial Immersion in an HMD-AR Serious Game for Museum Learning

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**Abstract:** Head-mounted display augmented reality (HMD-AR) can enrich museum-based game-based learning by situating interactive digital content in relation to physical exhibits, but may also distract visitors or shift attention away from interpretation. This paper investigates how flow, narrative, and spatial immersion relate to appreciation-related outcomes in an HMD-AR serious game for museum learning. We designed a coral-reef protection game in three variants, each foregrounding one immersive quality. In a between-subjects field study with 144 valid museum visitors, participants experienced one variant and completed questionnaires and short interviews. Results showed a differentiated pattern: the flow-enhanced variant showed the clearest alignment between design emphasis and perceived immersion, while the spatial-enhanced variant highlighted a tension between environmental richness and awareness of the surrounding museum space. Narrative immersion was associated with perceived meaning and educational value, whereas post-experience engagement intentions were mainly shaped by prior engagement. We argue that HMD-AR museum games should align specific immersive qualities with interpretation, attention, and meaning-making rather than maximize immersion as a generic goal.

**Keywords:** Game-based learning, HMD-AR, Museum learning, Serious games, Immersion, Flow immersion, Narrative immersion, Spatial immersion

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## 1. Introduction

Interactive and immersive technologies are used in museums to support interpretation, visitor engagement, and informal learning (Spadoni et al. 2022, Yun et al. 2023). HMD-AR is especially relevant because it can place digital content in direct spatial relation to physical exhibits (Hammady et al. 2020b, Liu et al. 2023). When combined with game-based learning, it can transform exhibition themes into situated serious game experiences in which visitors act, observe feedback, move through space, and encounter museum content through embodied interaction (Billinghurst et al. 2015, Falk and Dierking 2000).

A central design issue is not simply whether an HMD-AR experience is immersive, but what kind of immersion it produces (Pianzola et al. 2021). In this paper, we distinguish between flow, narrative, and spatial immersion as three experiential qualities that may co-exist but may also guide visitor attention and interpretation in different ways.

This distinction is important for museums. A strongly task-oriented game may hold attention but orient visitors toward completion rather than reflection (Taub et al. 2020). A narrative frame may connect actions to broader meanings and consequences (Naul and Liu 2020). Spatially rich AR may make content tangible, but may also remain decorative if not linked to interpretation (Hammady et al. 2020a). HMD-AR museum games therefore raise a practical design question: which immersive quality should be foregrounded, and how does it relate to appreciation, engagement, and possible downsides such as distraction or overwhelm?

This paper addresses this question through a field study of a coral-reef protection HMD-AR serious game in a natural history museum. The prototype was implemented in three variants: a flow-oriented version, a narrative-oriented version, and a spatial-oriented version. Each version shared the same topic and general interaction setting, but emphasized different design mechanisms. We examine whether these design emphases were reflected in visitors' perceived immersion and how flow, narrative, and spatial immersion related to appreciation-related outcomes.

Based on this design-oriented comparison, the study addresses two research questions:

*RQ1: To what extent do flow-, narrative-, and spatial-oriented design variants differ in visitors' perceived immersion?*

*RQ2: How do perceived flow, narrative, and spatial immersion relate to appreciation-related outcomes and engagement intentions?*

The paper contributes a field-based comparison of three immersion-focused HMD-AR serious game variants and empirical evidence on how immersion types relate to museum-relevant outcomes. It frames immersion type as a design lever that should be aligned with interpretive goals rather than treated as a generic benefit.

## **2. Related Work**

### **2.1 HMD-AR Serious Games in Museum Learning**

Museums are informal learning environments in which visitors engage with cultural, scientific, and natural heritage through voluntary and self-directed exploration (Staus et al. 2021). Visits are often brief, social, and shaped by prior interests (Li 2024). Digital media are therefore often used to attract attention, scaffold interpretation, and make complex topics accessible (Blunden 2020).

AR can enrich museum interpretation by overlaying digital labels, animations, simulations, or reconstructions onto physical exhibits (Martí-Testón et al. 2021). HMD-AR extends this potential through hands-free, first-person, and spatially situated interaction (Liu et al. 2023). By combining spatial tracking with embodied movement, digital content can be connected to visitors' positions and to objects in the exhibition space (Billinghurst et al. 2015, Dunleavy et al. 2009).

Serious games add goals, challenges, feedback, progression, and agency to learning experiences (Taub et al. 2020). In museums, these mechanics can encourage visitors to explore, solve problems, follow missions, or make decisions related to exhibition themes (DaCosta and Kinsell 2023). However, public museum settings also involve limited time, movement, social interaction, device comfort issues, and varied familiarity with HMDs (Trunfio et al. 2020). Evaluation therefore needs to consider not only enjoyment and usability, but also the balance between gameplay, exhibit attention, and interpretation.

### **2.2 Immersion as a Multidimensional Construct**

Immersion is widely used in games, AR, VR, and interactive media, but the term can refer to several aspects of experience, including absorption, involvement, presence, sensory richness, and interactivity (Brown and Cairns 2004, Pianzola et al. 2021). In this study, immersion is treated as a multidimensional experiential construct consisting of flow, narrative, and spatial immersion.

Flow immersion refers to absorption in goal-directed activity supported by clear goals, manageable challenge, feedback, and sustained concentration (Csikszentmihalyi 1990, Rheinberg et al. 2003). Narrative immersion refers to involvement in a story, interpretive frame, or meaningful situation that helps visitors understand why their actions matter (Naul and Liu 2020). Spatial immersion refers to the feeling of being situated with digital content in physical space, supported by spatially anchored 3D content, viewpoint-dependent perception, and embodied exploration (Bhowmik 2024).

These immersion types are not mutually exclusive. A single HMD-AR experience can involve task focus, story framing, and spatial presence at the same time. Nevertheless, different design choices can foreground different immersive qualities, making immersion not only an evaluation construct but also a design variable.

### **2.3 Immersion, Appreciation, and Risks**

Immersion is often assumed to support learning because it can increase attention, motivation, emotional involvement, and memory (Parong and Mayer 2021). In HMD-AR museums, it may also make distant or abstract phenomena more tangible (Spadoni et al. 2022). However, more immersion does not automatically lead to better appreciation. A highly engaging game may focus visitors on task completion, while visually rich AR may be remembered as spectacle without supporting deeper interpretation. Interaction demands may also increase cognitive load (Noetel et al. 2022).

Different immersion types may therefore contribute differently to museum outcomes. Immersive design can support attention, meaning-making, and situated perception, but these benefits depend on whether the immersive elements are connected to interpretation rather than functioning mainly as task pressure or visual spectacle. Prior work has shown the potential of AR and game-based learning in museums, but immersion is often treated as a single experiential quality. This study addresses that gap by comparing three HMD-AR variants in the same exhibition context.

### **3. Methodology**

This study follows a Research-through-Design-informed methodology (Zimmerman et al. 2007). Rather than evaluating an existing museum application, we used the design and evaluation of an HMD-AR serious game prototype as a way of generating knowledge through making. The prototype functioned as a research artefact for investigating how flow, narrative, and spatial immersion can be foregrounded in museum-based game-based learning and how these immersive qualities relate to appreciation-related outcomes.

The prototype concept was developed in consultation with museum stakeholders, including curatorial and educational practitioners. Through several exchanges, the exhibition topic, interpretive focus, information density, and feasible interaction scenario were aligned with the museum context. The resulting coral-reef protection scenario was therefore not only a technical demonstrator, but a situated design artefact shaped by exhibition content, spatial layout, visitor conditions, and educational goals.

The methodological logic combined design variation with field evaluation. Based on the same exhibition topic and comparable content structure, three variants were created to foreground flow, narrative, or spatial immersion. These design emphases were informed by the physical exhibition setting, the selected exhibits, the amount of interpretive information to be communicated, and the appropriate difficulty of an action-based HMD-AR game in a public museum environment. The field study then examined whether these design intentions were reflected in visitors' perceived immersion and how the three immersion types related to appreciation-related and museum-learning-related outcomes.

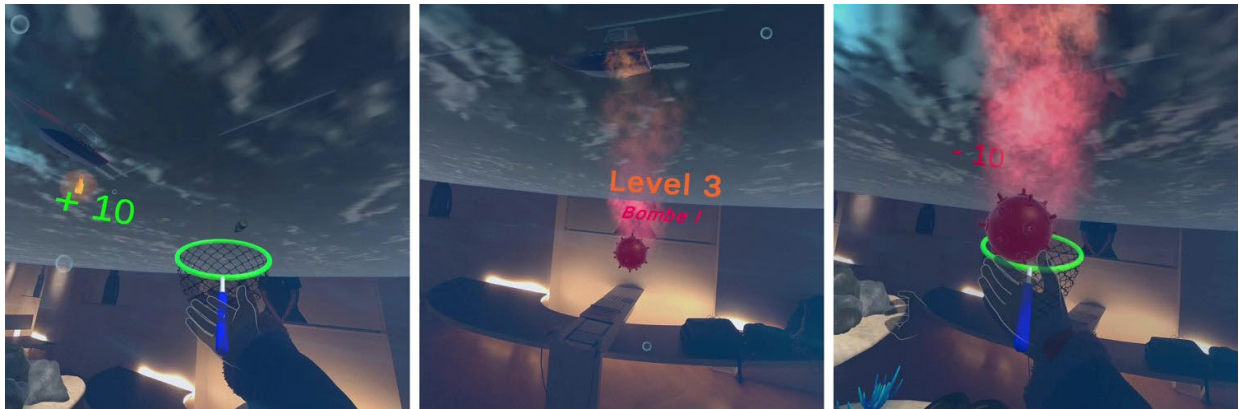
### **4. Prototype and Implementation**

#### **4.1 Museum Context and Learning Topic**

The prototype was designed for a natural history museum exhibition context and focused on coral-reef protection. Coral reefs are ecologically significant but vulnerable ecosystems affected by pollution, climate change, human activity, and broader environmental change (Hughes et al. 2003). As a museum learning topic, coral-reef protection is suitable for an HMD-AR serious game because it combines visually rich environmental content with clear educational messages about threats, consequences, and protective actions. The experience was designed for short walk-up public use. In each user session, the prototype first introduced the coral-reef exhibit and explained that human activity threatens reef survival. Visitors then entered a game phase in which marine litter fell from fishing boats above the reef, they raised their arm to catch the litter with a virtual fishing net, linking the physical action to the ecological message that human-generated waste can damage coral reefs. The explanatory part was mainly based on watching and listening, while the game part used simple arm-based interaction. The prototype was implemented in Unity and deployed on Meta Quest 3 passthrough AR. All three variants used the same hardware, interaction setup, and session structure, with active experience time kept below five minutes.

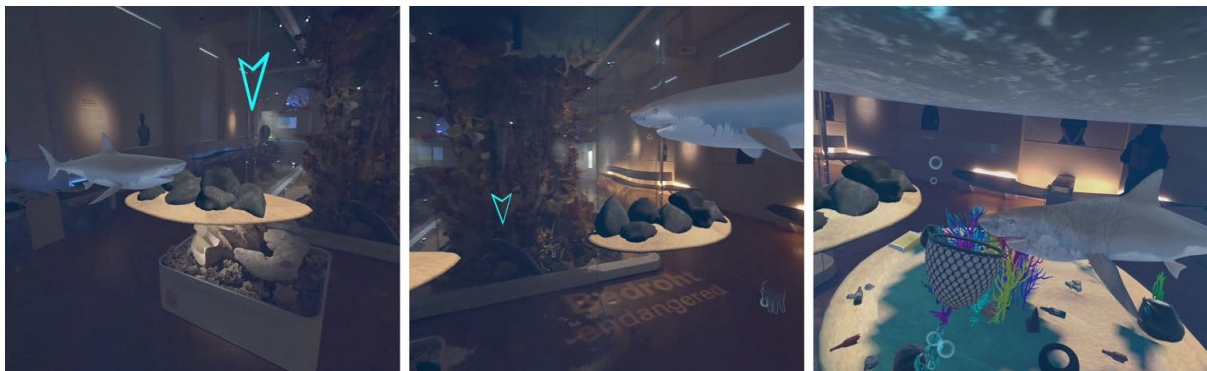
#### **4.2 Design Variants**

The flow-enhanced variant targeted goal-directed interaction, challenge structure, and immediate feedback. It introduced clearer tasks, progression, and multiple difficulty levels. Marine litter fell at increasing speed across levels, and later levels added distractor objects that required participants to distinguish correct from incorrect actions. The design intention was to support focused task engagement and responsiveness. Representative screenshots of the flow-enhanced variant are shown in Figure 1.



**Figure 1: Representative screenshots of the flow-enhanced variant. Left: successfully catching marine litter during gameplay awards +10 points. Middle: the game includes three difficulty levels. Right: catching a bomb results in a penalty of -10 points**

The narrative-enhanced variant targeted story framing, character guidance, and causal explanation. A shark avatar guided participants through the coral-reef protection scenario and framed the activity as a meaningful mission. Narrative feedback explained why the reef was under threat, why the participants' actions mattered, and how in-game events related to broader ecological consequences. Figure 2 illustrates representative scenes from the narrative-enhanced variant.



**Figure 2: Representative screenshots of the narrative-enhanced variant. Left and middle: a shark avatar introduces exhibit-related content to the user in front of different museum exhibits. Right: the shark avatar provides the user with a virtual net for collecting marine litter in the game**

The spatial-enhanced variant targeted environmental richness, embodied exploration, and the feeling of being situated with reef-related content. It incorporated additional underwater effects, reef plants, animals, ambient media, and spatially distributed digital elements. The design intention was to make the reef environment feel tangible and explorable. Figure 3 illustrates representative scenes from the spatial-enhanced variant.



**Figure 3: Representative screenshots of the spatial-enhanced variant. Left, middle, and right: additional seaweed, corals, fish, and other marine elements are distributed across different locations, accompanied by ambient sound effects to enhance the underwater atmosphere**

## 5. Evaluation and Results

### 5.1 Evaluation Design and Participants

The evaluation was structured around the two research questions. The design-emphasis check addresses whether the three variants differed in perceived immersion, while the regression and pre-post engagement analyses examine how the immersion dimensions related to appreciation-related outcomes and engagement intentions.

We conducted a between-subjects field study in the museum setting, combining pre- and post-experience questionnaires with short semi-structured interviews. Each participant experienced one of the three variants, reducing carry-over effects. The final dataset included  $N = 144$  valid participants: flow-enhanced variant ( $n = 46$ ), narrative-enhanced variant ( $n = 52$ ), and spatial-enhanced variant ( $n = 46$ ). Participants were recruited on site through researcher invitation or by approaching the study station, participation was voluntary and anonymous. The variants were tested on separate days, with each variant deployed for one to two days. Because the study was anonymous, repeat participation across variants could not be completely ruled out, but no repeat participation was observed or reported.

Eligible participants were adults aged 18 years or older who could use the HMD-AR prototype and perform the required interaction. We collected basic demographic and background information, including age group, gender, and prior experience with AR, digital games, and museum visits. After consent, participants completed a pre-questionnaire, received a brief headset and interaction introduction, experienced one assigned variant for less than five minutes, and completed a post-questionnaire and short interview.

### 5.2 Measures and Data Analysis

The questionnaire included adapted standardized immersion measures and self-developed study-specific judgment items. Flow (Rheinberg et al. 2003), narrative (Appel et al. 2015), and spatial immersion (Hartmann et al. 2016) were adapted from established scales. The self-developed items were used as pragmatic field-study indicators rather than validated psychometric scales, capturing appreciation-related outcomes, engagement intentions, and possible downsides of using HMD-AR in a museum context. Table 1 summarizes the measured constructs and the corresponding item focus used in the questionnaire.

**Table 1: Summary of questionnaire measures**

| Measure / construct                | Item focus                                                                                              |
|------------------------------------|---------------------------------------------------------------------------------------------------------|
| Flow immersion                     | Task absorption, concentration, challenge, feedback, and worry about failure                            |
| Narrative immersion                | Story involvement, interpretive framing, and perceived connection between action and meaning            |
| Spatial immersion                  | Spatial presence, situatedness, and involvement with AR content in the physical exhibition space        |
| Experience quality                 | Enjoyment, recommendation intention, and interest in future AR-glasses-based exhibitions                |
| Meaning / educational value        | Perceived meaningfulness and perceived usefulness of digital games for communicating scientific content |
| Negative experience                | Distraction from the actual exhibition and feeling overwhelmed                                          |
| Social limitation                  | Feeling isolated, playing alone, and being unable to directly share the experience with others          |
| Engagement intention               | Intention to take a closer look at the coral-reef exhibition and to seek further information            |
| Topic interest / duration judgment | Interest in the coral-reef topic and perceived appropriateness of the experience duration               |

Accordingly, study-specific indicators were analysed as single items or as composite scores only where items addressed closely related aspects of the visitor experience.

Quantitative data were analysed using descriptive statistics, Cronbach's alpha, one-way ANOVAs with post-hoc comparisons, and multiple regression models. ANOVAs tested whether the three variants differed in perceived flow, narrative, and spatial immersion. Regression models examined the relative contribution of each immersion

type to appreciation-related outcomes and engagement intentions. A baseline-controlled regression model tested whether immersion types explained post-experience engagement intention beyond pre-experience engagement. Interview responses were analysed thematically to contextualize the questionnaire results (Terry et al. 2017).

### 5.3 Scale Reliability and Descriptive Overview

Before addressing the research questions, we examined the internal consistency of the three adapted immersion subscales. All scales showed acceptable reliability: flow immersion (10 items, Cronbach's  $\alpha = 0.76$ ), narrative immersion (6 items,  $\alpha = 0.75$ ), and spatial immersion/presence (13 items,  $\alpha = .79$ ). Average scale scores were therefore computed for each participant.

Across all participants ( $N = 144$ ), mean scores were relatively high for all three immersion types: flow immersion ( $M = 3.83$ ,  $SD = 0.52$ ), narrative immersion ( $M = 3.66$ ,  $SD = 0.64$ ), and spatial immersion ( $M = 3.52$ ,  $SD = 0.54$ ).

### 5.4 Design-emphasis Check

To examine whether the design emphases were reflected in participants' perceived immersion, we compared the three conditions on flow, narrative, and spatial immersion. Table 2 presents the mean scores, standard deviations, and ANOVA results.

**Table 2: Design-emphasis check for immersion scores by variant**

| Measure             | Flow variant<br>M(SD) | Narrative variant<br>M(SD) | Spatial variant<br>M(SD) | ANOVA / post-hoc                                                         |
|---------------------|-----------------------|----------------------------|--------------------------|--------------------------------------------------------------------------|
| Flow immersion      | 3.95 (0.59)           | 3.86 (0.45)                | 3.69 (0.50)              | $F(2,141)=3.06$ , $p=0.050$ , $\eta^2=0.042$ , Flow > Spatial, $p=0.044$ |
| Narrative immersion | 3.72 (0.61)           | 3.73 (0.67)                | 3.51 (0.61)              | $F(2,141)=1.87$ , $p=0.158$ , $\eta^2=0.026$ , n.s.                      |
| Spatial immersion   | 3.72 (0.46)           | 3.52 (0.54)                | 3.31 (0.56)              | $F(2,141)=7.03$ , $p=0.001$ , $\eta^2=0.091$ , Flow > Spatial, $p=0.001$ |

The ANOVA results should be interpreted as a design-emphasis check rather than as evidence that the three immersion types were cleanly isolated. The flow-enhanced variant produced the highest flow score, with a borderline condition effect and a significant post-hoc difference between the flow- and spatial-enhanced variants. This was consistent with the design intention, but indicates only a tendency.

Narrative immersion did not differ significantly between variants. Spatial immersion showed a significant condition effect, but in the opposite direction to the design intention: the spatial-enhanced variant produced the lowest spatial immersion score. Overall, the results indicate a differentiated pattern in which immersive qualities emerged from the interaction between task structure, narrative framing, spatial content, and visitor interpretation.

### 5.5 Immersion Types and Appreciation-Related Outcomes

To examine how the three immersion types related to appreciation-related outcomes, we conducted multiple linear regression analyses with flow, narrative, and spatial immersion entered simultaneously as predictors. The outcome variables included experience quality, meaning and educational value, negative experience, social limitation, post-experience engagement intention, engagement change, and post-experience coral-reef interest. Table 3 summarizes the regression models and their main interpretations.

**Table 3: Summary of regression results linking immersion types to appreciation-related outcomes and engagement intentions**

| Outcome                     | Model result                                                     | Main interpretation                                                                                               |
|-----------------------------|------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| Experience quality          | $R^2 = 0.020$ , no significant immersion predictor               | General experience quality was not strongly determined by one specific immersion type.                            |
| Meaning / educational value | $R^2 = .039$ , narrative immersion $\beta = 0.221$ , $p = 0.034$ | Narrative immersion showed the clearest modest contribution to meaning- and educational-value-related evaluation. |
| Negative experience         | $R^2 = 0.029$ , no conventional significant immersion predictor  | Immersion did not clearly translate into distraction, overload, or other negative experience indicators.          |

| Outcome                              | Model result                                                                                                                                | Main interpretation                                                                                                                  |
|--------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| Social limitation                    | $R^2 = 0.013$ , no significant immersion predictor                                                                                          | The perceived social limitation of the HMD-AR experience was not clearly associated with one immersion type.                         |
| Engagement change                    | $R^2 = 0.010$ , no significant immersion predictor                                                                                          | Changes in engagement intention from pre- to post-experience were not clearly explained by the three immersion types.                |
| Post-experience coral-reef interest  | $R^2 = 0.012$ , no significant immersion predictor                                                                                          | Post-experience topic interest was not strongly predicted by flow, narrative, or spatial immersion.                                  |
| Post-experience engagement intention | Baseline-controlled model: $R^2 = 0.505$ , baseline engagement $\beta = 0.689$ , $p < .001$ , no additional significant immersion predictor | Post-experience engagement intention was mainly explained by participants' prior engagement intention rather than by immersion type. |

Overall, the relationships between immersion types and post-experience outcomes were selective and limited. The clearest result concerned meaning and educational value: narrative immersion was the only significant predictor,  $\beta = 0.221$ ,  $p = 0.034$ , although the explained variance was small ( $R^2 = 0.039$ ). Flow and spatial immersion did not show significant unique contributions.

Given the exploratory nature of the regression analyses and the number of tested outcomes, this association should be interpreted as a modest indication rather than strong predictive evidence. For the other outcomes, the models explained little variance and no immersion type emerged as a consistent significant predictor.

## 5.6 Pre-post Engagement Intentions

The questionnaire measured visitors' intentions to take a closer look at the coral-reef exhibition and to seek further information before and after the HMD-AR experience. Engagement intentions were already moderately high before the experience ( $M = 3.48$ ,  $SD = 0.79$ ) and increased slightly afterwards ( $M = 3.74$ ,  $SD = 0.74$ ,  $M$  change =  $0.26$ ,  $SD = 0.59$ ).

A baseline-controlled regression showed that pre-experience engagement intention was the dominant predictor of post-experience engagement,  $\beta = .689$ ,  $p < .001$ . Flow, narrative, and spatial immersion did not explain additional variance. Thus, the pre-post engagement indicators were treated as secondary outcomes rather than strong evidence that any specific immersion type increased engagement.

## 5.7 Qualitative Findings: Visitor Reflection and Appreciation

The short interviews contextualized the questionnaire results. Three recurring themes were identified: awareness of coral-reef threats, meaning-making through interaction, and memorable immersive features. Participants mentioned pollution, climate change, human impact, protective actions, visual AR elements, narrative explanations, and game tasks. These responses suggest that the prototype communicated the general message of coral-reef vulnerability and protection. They also indicate that memorable interaction alone did not necessarily lead to deeper appreciation, what mattered was whether immersive elements helped visitors connect their actions and observations to the exhibition topic.

# 6. Discussion

## 6.1 Immersion as an Emergent Design Outcome

The results suggest that immersion in HMD-AR museum games is not a single outcome or an automatic result of adding corresponding features. Instead, it emerged from the interaction between task structure, narrative framing, spatial content, and the museum context. This supports a multidimensional view of immersion while showing that its types are not independently controllable in situated museum use.

The unexpected spatial result is important. Unlike fully virtual VR, passthrough AR keeps digital content connected to the real museum environment. In the spatial-enhanced variant, richer underwater effects and distributed virtual content may have increased awareness of surroundings and real-virtual relations. This can support safety, orientation, and exhibit attention, but may reduce perceived immersion in the virtual reef scene. Spatial immersion in HMD-AR should therefore not be equated with adding more environmental media, spatial content must guide attention toward interpretive relationships between the exhibit, virtual scene, and visitors' actions.

## **6.2 Narrative Immersion and Meaning-making**

Narrative immersion showed the clearest association with meaning and educational value. One explanation is that narrative framing helped participants understand why their actions mattered. In the coral-reef protection game, narrative elements connected threats, actions, and consequences, making the experience feel more meaningful and educationally valuable.

This suggests that narrative immersion functioned less as storytelling than as an interpretive mechanism linking interaction to meaning. However, narrative immersion did not predict post-experience engagement intention after controlling for baseline engagement. It should therefore be interpreted mainly as supporting meaning-making and perceived educational value, rather than as a direct driver of all learning-related outcomes.

## **6.3 Design Implications**

The findings suggest that designers should not simply maximize immersion. More visual richness, interaction, or narrative content does not automatically lead to stronger appreciation or engagement. Instead, designers should ask which type of immersion is needed for a specific interpretive goal. Narrative immersion can connect gameplay to museum meaning through missions, character guidance, causal explanation, and interpretive feedback. Flow immersion can support focus through goals, challenge, and feedback, but should remain linked to educational interpretation. Spatial immersion should help visitors notice relationships between physical and virtual elements, rather than adding environmental richness as decoration.

## **6.4 Limitations and Future Work**

The real museum setting increased ecological validity but reduced experimental control, as visitor flow, time pressure, prior interest, and familiarity with HMD-AR may have influenced the results. The variants foregrounded different immersion types but did not isolate them completely, so the findings should be interpreted as differences between design emphases rather than pure manipulation effects. The study also relied mainly on immediate self-report measures and did not capture long-term learning, retention, or behavioural change. In addition, the variants were deployed on separate museum days rather than being fully randomized within the same period, so differences in visitor composition, crowding, or situational context may have influenced condition comparisons.

Further research should examine other exhibition domains and investigate how narrative guidance, task difficulty, and spatial complexity can be balanced for different visitor needs without increasing distraction or overload.

## **7. Conclusion**

This paper compared three coral-reef HMD-AR serious game variants around flow, narrative, and spatial immersion in a museum field study with 144 valid participants. The findings show that immersion types cannot be reliably produced simply by adding corresponding design features. The flow-enhanced variant showed the clearest expected tendency, while the narrative- and spatial-enhanced variants revealed more complex patterns. In particular, the spatial-enhanced variant suggests that environmental richness may increase awareness of the surrounding museum space rather than directly strengthen spatial immersion.

Outcome analyses indicate that narrative immersion was most clearly associated with perceived meaning and educational value, while engagement intentions were largely shaped by prior engagement. Overall, the study frames immersion type as a design lever for balancing engagement, attention, and meaning-making, rather than as a generic goal to be maximized.

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**Ethics Declaration:** Formal ethical clearance was not required for this anonymous, low-risk field study under the applicable institutional procedures. Participation was voluntary, and participants were informed about the purpose and procedure of the study before taking part. Only adult visitors were eligible to participate. No personally identifying data were collected, and the questionnaire and interview responses were analysed anonymously.

**AI Declaration:** AI-assisted tools, including DeepL and ChatGPT, were used during the preparation of this paper for language editing, grammar checking, sentence-level refinement, and formatting support. The research idea, study design, prototype development, data collection, analysis, interpretation, and final academic claims are the original work of the authors. All AI-assisted suggestions were reviewed and approved by the authors, who take full responsibility for the final paper.

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