

EVALUATION OF USER PERCEPTION IN VIRTUAL REALITY: 3D GAUSSIAN SPLATTING FOR THE DESIGN OF IMMERSIVE EXPERIENCES

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Abstract

In digital heritage, emerging approaches for generating photorealistic image-based 3D models, even via low-cost devices as smartphones, have gained significant attention. Among these approaches, 3D Gaussian Splatting (3DGS) offers notable improvements in visual fidelity and realism. Despite extensive evaluation through quantitative metrics and benchmark comparisons with photogrammetry, the potential of 3DGS for immersive navigation in Virtual Reality (VR) – particularly from a user experience perspective – is underexplored. The paper presents a comparative study of photogrammetry and 3DGS within a dedicated VR exploration framework applied to a heritage scene. Participants assess perceived visual fidelity, realism, spatial coherence, and interaction comfort in environments reconstructed with both techniques, revealing perceptual differences that are relevant for experiential and design-oriented approaches to immersive representation.

Keywords

Gaussian Splatting, Virtual Reality, Immersive Environments, User Experience, Representation paradigms

1. Introduction

Recent years have witnessed significant advances in 3D reconstruction techniques, enabling the creation of accurate digital representations of real-world scenes (Bianconi et al., 2023). Photorealistic models can now be generated using low-cost acquisition devices such as smartphones, demonstrating a democratization of data capture workflows that reveals particularly relevant in the field of Cultural Heritage, where scalable, reproducible, and cost-efficient documentation strategies are essential.

Established photogrammetric workflows rely on Structure-from-Motion (SfM) and Multi-View Stereo (MVS) to reconstruct explicit mesh geometry and subsequently texture it to achieve visually realistic results (De Fino et al., 2023); neural renderings (Mildenhall et al., 2020) encode scene information within neural networks, learning view-dependent appearance directly from images. Besides such techniques, 3D Gaussian Splatting (3DGS) adopts a continuous point-based representation to model the scene as a set of anisotropic 3D Gaussians carrying radiance and opacity information, enabling efficient differentiable rendering (Kerbl et al., 2023).

The 3DGS formulation combines the explicitness of point-based methods with the view-dependent appearance modelling typical of neural approaches, producing photorealistic renderings while maintaining reduced memory footprint and high scalability. Recent research has explored the application of Gaussian Splatting to the visualization of Cultural Heritage artifacts and sites. While numerous studies have benchmarked 3DGS methods using quantitative metrics for reconstruction accuracy (Fadilah et al., 2026; Billi, Caroti, et al., 2025), less attention has been paid to how these models are perceived by users in immersive contexts.

At the same time, several methods are emerging to integrate 3DGS into Virtual Reality (VR) environments, which provide an ideal framework for assessing user experience through embodied exploration and interaction, e.g., in cultural heritage visualization, virtual tourism, and interactive storytelling. In such contexts, perceptual factors—including visual fidelity, spatial coherence, lighting consistency, and interaction comfort—directly influence user satisfaction and sense of presence.

However, the design and evaluation of VR experiences based on 3DGS models remain largely unaddressed.

Addressing this issue, this paper presents a comparison of mesh-based photogrammetry and 3DGS from a user-centred perspective. Through a structured VR study and a questionnaire grounded in established human-computer interaction methodologies, the work analyses how differences in representation affect perceived realism, immersion, and usability of cultural heritage sites.

2. Related work

2.1 Reconstruction of digital heritage scenes: Gaussian Splatting and Virtual Reality

In the digital heritage field, most VR exploration experiences still rely on textured meshes generated through photogrammetric reconstructions (Dhanda et al., 2019; Mezzino, 2023; Stanga et al., 2023). However, recent research identified 3D Gaussian Splatting (3DGS) as a promising paradigm for real-time, photorealistic 3D scene representation, with increasing relevance for virtual and extended reality (VR/XR) applications.

First introduced by Kerbl et al. (2023), 3DGS is a rendering technique that represents scenes as a collection of 3D Gaussians functions. Such functions are efficiently optimized during rendering (*differentiable*) and turned into 2D images (*rasterized*) via an alpha blending technique. The properties of the Gaussians, as position, opacity, shape and colour, are optimized during training, to obtain a compact and accurate representation of the scene. The real-time rendering of novel views is finally achieved via a fast GPU sorting algorithm.

3DGS has rapidly gained adoption across various domains (Chen & Wang, 2025), including documentation and visualization of cultural artefacts and architectural heritage (Basso et al., 2024; Billi, Caroti, et al., 2025; Clini et al., 2024). In challenging conditions, including reflective materials, low-texture surfaces, and complex lighting scenarios, 3DGS-based models tend to reduce common artefacts associated with mesh reconstruction, favouring a perceptually stable representation (Billi, Croce, et al., 2025; Sommer et al., 2025; Yu et al., 2025).

Recent advances in view-consistent rendering for VR have focused on improving stability, latency, and stereoscopic coherence: VRSplat (Tu et al., 2025) enhanced robustness and rendering stability in VR, addressing key challenges like latency, temporal artifacts, and stereo mismatches.

Similarly, VR-GS (Jiang et al., 2024) introduced physics-aware and interactive Gaussian Splatting systems, enabling dynamic scene interaction. GaussianShopVR (Shen et al., 2025) demonstrated how 3DGS can support immersive 3D editing workflows, lowering the barrier for content generation in VR. In parallel, broader XR-oriented analyses (Qiu et al., 2025) highlighted the potential of 3DGS as a unifying representation for real-time applications across VR. Beyond the aspects of accuracy and precision, and considering applications in the architectural heritage domain, Jamil & Brennan (2025) further explored the perceptual and aesthetic dimensions of GS models, arguing that the technique produces a distinctive visual language that differs from traditional photogrammetry, potentially enhancing the sense of presence in immersive environments. Interactive virtual tours based on GS models are also emerging across several domains: Apopei (2025) applied them to multi-scale objects visualization in geosciences, Khedr et al. (2025) to virtual museum environments, while Shrestha et al. (2026) proposed an interactive web-based viewer to support the exploration of 3DGS models, integrating navigation functionalities with a map-based interface to enhance user orientation and interaction.

Since GS relies on point-based Gaussian primitives rather than conventional mesh representations, its integration within VR exploration frameworks is mediated by real-time engines as Unity and Unreal Engine: custom pipelines are developed for rendering, interaction design, and deployment on head-mounted displays. Open-source projects such as Gsplat (github.com/wuyize25/gsplat-unity) and UnityGaussianSplatting (github.com/arasp/Unity-GaussianSplatting) currently support navigation and basic scene exploration.

While interaction capabilities remain limited, these tools represent an important bridge between advances in 3D representation and their application in VR-based immersive evaluation.

2.2 User Experience Evaluation in Virtual Reality

Several specialized evaluation frameworks and questionnaires have been developed to assess user experience in immersive virtual environments, accounting for the unique characteristics of VR interactions.

Bareišytė et al. (2024) conducted a systematic scoping review of questionnaires for evaluating VR

experiences, identifying the diversity of instruments and domains they address. The work highlighted the need for validated context-appropriate measurement tools.

Tcha-Tokey et al. (2016) proposed a comprehensive questionnaire specifically designed to measure user experience in terms of immersion and usability.

Chertoff et al. (2010) developed the Virtual Experience Test (VET), a virtual environment evaluation questionnaire that assesses the experiential components unique to VR, including presence, engagement, and immersion factors.

These evaluation frameworks provide standardized approaches for measuring subjective responses to VR experiences, enabling systematic comparison across different rendering techniques and application contexts.

3. Materials

To evaluate the comparative qualities of textured mesh and 3DGS rendering in a meaningful context, the interiors of the grand amphitheatre of the Arts et Métiers Engineering campus in Aix-en-Provence are set as the target reconstruction scene (Fig. 1). The building, currently scheduled for renovation, represents a significant architectural landmark with both cultural and institutional value, making it particularly relevant for high-fidelity digital preservation. Its interiors are characterized by complex geometries, including ornate architectural details and heterogeneous surface materials, thus providing a challenging test case for both reconstruction techniques.

The imminent renovation further underscores the importance and timeliness of this digital documentation. Concerning the data acquisition step, videos were acquired by a Xiaomi Redmi Note 12 Pro+, equipped with a 200 MP sensor (Samsung ISOCELL HPX) with optical image stabilization (OIS) to ensure capture stability. Recordings were performed at a resolution of 1080p and a frame rate of 60 fps, in order to maximize image overlap between consecutive frames during user movement and to reduce the likelihood of motion blur. Frames exhibiting visible blur were excluded during the image selection stage prior to processing.

Since the acquisition simulates a freely moving user, the camera-object distance varies between approximately 1 and 7 meters. Consequently, the GSD is not constant and changes dynamically along



Fig. 1: The interiors of the amphitheatre

the trajectory, within the range 0,20 – 1,05 mm/pixel.

For model generation, experiments were conducted on a workstation featuring an AMD Ryzen 7 7800X3D CPU, an AMD Radeon RX 7900 XTX GPU with 24 GB VRAM, and 32 GB RAM.

The acquired data of the amphitheatre were used to generate two distinct scene representations —photogrammetric and 3DGS— which were subsequently integrated into a VR environment to enable a user-centred evaluation.

The experimental protocol involved a sample of 20 participants, who were asked to explore both environments with a Meta Quest 3 VR headset and two motion controllers and subsequently complete a user experience questionnaire.

4. Methods

The proposed methodology (Fig. 2) provides a controlled framework for the comparative evaluation of photogrammetry and 3DGS, ensuring identical input data and camera parameters.

Image data are acquired using low-cost smartphone devices, and the pipeline is organized into five main stages: data acquisition, alignment, model reconstruction via photogrammetry or 3DGS, post-processing, and VR integration.

The process begins with video acquisition of the target scene using a smartphone, ensuring uniform coverage at a constant speed and from multiple viewpoints to avoid gaps in spatial information. This approach follows established practices for heritage documentation via photogrammetry (Dhanda et al., 2019).

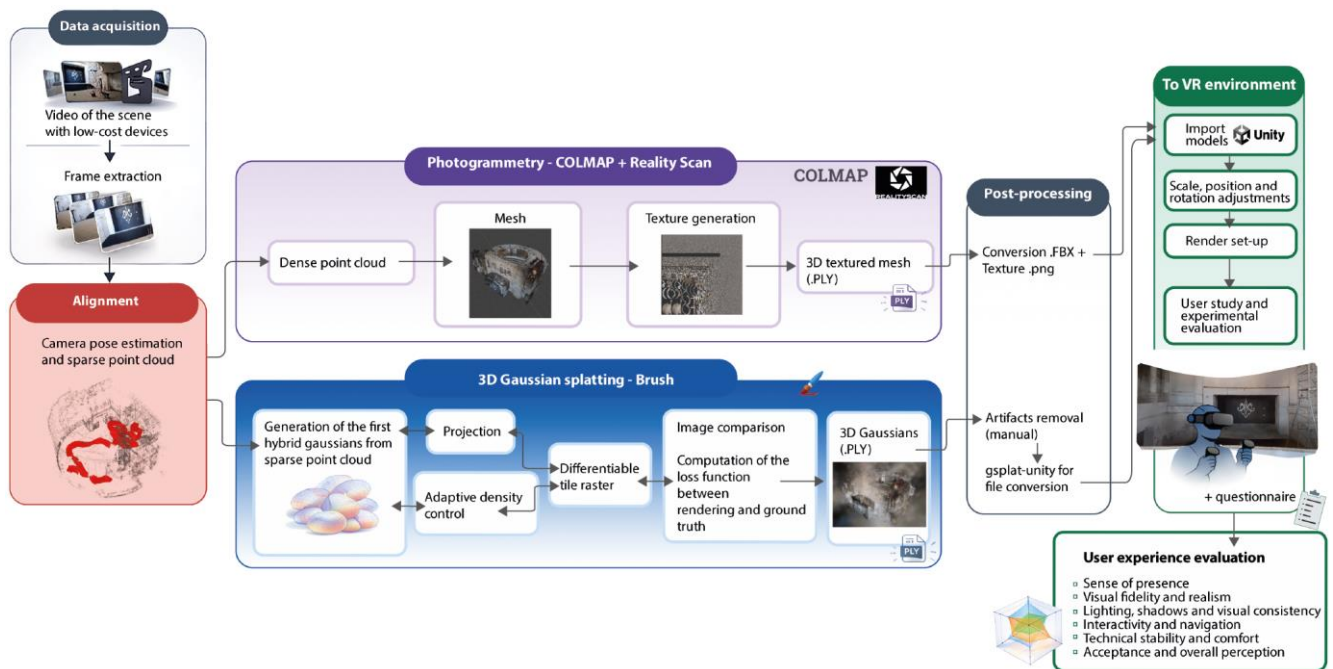


Fig. 2: Proposed methodological approach

The recorded video is then processed using FFmpeg to extract individual frames, with the sampling rate adjusted to balance reconstruction quality and computational efficiency.

Feature extraction and matching are performed using the open-source SfM pipeline COLMAP; starting from the reconstruction of camera poses, a sparse 3D point cloud is generated based on the extracted frames, serving as foundation for model reconstruction workflows and ensuring consistency in input data and alignment.

Leveraging the sparse point cloud, the pipeline diverges into two parallel workflows corresponding to the two rendering techniques under comparison: photogrammetry and 3DGS for the same 3D scene and based on the same set of input images.

For the case of photogrammetry, the alignment parameters from COLMAP are imported into RealityScan, where MVS reconstruction is applied to generate a dense point cloud. The latter is subsequently converted into a textured triangulated mesh, which is exported in FBX format with associated texture maps for compatibility with game engines. The workflow reflects standard photogrammetric reconstruction practices, where textured meshes remain the dominant representation, particularly in cultural heritage applications (Murtiyoso et al., 2024).

The Gaussian splatting approach branches from the same sparse reconstruction: the camera

orientation parameters and original extracted images are imported into the 3DGS reconstruction engine Brush (<https://github.com/ArthurBrussee/brush>). By exploiting the technology by Kerbl et al. (2023), the system optimizes a set of 3D Gaussians to represent the scene, where each Gaussian is characterized by its position, covariance (defining size and orientation), opacity, and spherical harmonic coefficients (encoding view-dependent colour).

The trained Gaussian representation is exported as a PLY file containing the parameters of all Gaussians. This file is then loaded into SuperSplat Editor, a web-based tool for Gaussian visualization and editing, where artefacts and outlier Gaussians are manually removed to improve visual quality.

Both representations are then integrated into a unified VR environment using Unity’s built-in render pipeline. The photogrammetric model is directly imported as an FBX mesh with its texture, while the 3DGS model is processed through the *gsplat-unity* plugin, which converts the Gaussian data into Unity-compatible assets for real-time rendering.

The Gaussian Splatting representation and the textured mesh are required to occupy identical positions and orientations within the virtual environment to enable direct comparison. To this task, the two models are scaled based on control points of known distance placed on scene at the time of data capture, and roto-translations are

Tab. 1: Questionnaire structure

Section	Dimension	Items	Scale	Reference
1	Sense of presence	3	7-point Likert	(Chertoff et al., 2010; Tcha-Tokey et al., 2016)
2	Visual Fidelity and Realism	5	7-point Likert	(Chertoff et al., 2010; Tcha-Tokey et al., 2016)
3	Lighting, Shadows, and Visual Consistency	5	7-point Likert	Custom
4	Interactivity and Navigation	5	7-point Likert	Custom
5	Technical stability and Comfort	3	7-point Likert	Custom
6	Acceptance and Overall Perception	5	7-point Likert	(Bareišytė et al., 2024; Chertoff et al., 2010)
7	Open-ended questions	5	Open-ended	Custom

manually performed within Unity to ensure perfect spatial correspondence between the two models. As such, the pipeline supports a controlled comparison of user experience in VR by maintaining identical input data and spatial alignment.

Based on this, a within-subject experimental design is adopted, whereby participants experience both representations sequentially using a head-mounted VR headset and subsequently complete a user experience questionnaire developed on established VR evaluation frameworks. In detail, the evaluation questionnaire is designed following a hybrid approach: on the one hand, it draws upon established VR user experience assessment frameworks (Bareišytė et al., 2024; Chertoff et al., 2010; Tcha-Tokey et al., 2016); on the other hand, it incorporates criteria tailored to the specific characteristics and objectives of the case study (Tab. 1). Participants rate a series of statements on a 7-point Likert scale (1 = Strongly Disagree; 7 = Strongly Agree), evaluating each rendering technique separately based on the following constructs (Tab. 1):

1 – Sense of Presence: the degree of immersion and the extent to which participants feel present within the virtual environment, including their perception of spatial realism and detachment from the physical world.

2 – Visual Fidelity and Realism: the perceived visual quality of the scene, including the accuracy of textures, geometric detail, surface definition, and overall credibility of the environment.

3 – Lighting, Shadows, and Visual Consistency: the realism and coherence of lighting conditions,

including illumination consistency, shadow behaviour, and the absence of visual artefacts affecting scene perception.

4 – Interactivity and Navigation: the usability of the VR system in terms of navigation, movement fluidity, and interaction mechanisms supporting exploration and enhancing immersion.

5 – Technical Stability and Comfort: the technical performance of the experience, focusing on smoothness, absence of latency or stuttering, and user comfort, to evaluate, e.g., visual fatigue or motion sickness.

6 – Acceptance and Overall Perception: overall user judgment of the experience, including perceived satisfaction and preference.

In addition, eventual qualitative feedback is demanded via open-ended questions, providing deeper insights into user perception beyond quantitative ratings.

For each construct, descriptive statistics (mean, standard deviation, and median) are calculated for both Photogrammetry and 3DGS conditions. Mean differences are computed as:

$$\Delta = \text{Mean}_{3DGS} - \text{Mean}_{\text{Photogrammetry}} \quad (1)$$

Since all participants evaluate both conditions, statistical comparisons are performed using the Wilcoxon signed-rank test (Wilcoxon, 1945). Effect sizes are estimated using the rank-biserial correlation. To account for multiple comparisons across the 6 constructs, *p*-values are finally adjusted using the Bonferroni-Holm correction (Holm, 1979), with statistical significance set at *p* < 0.05.

Tab. 2: Pipeline comparison

Stage	Textured mesh - Photogrammetry	3D Gaussian Splatting
Alignment	COLMAP	COLMAP
Reconstruction	Reality Scan (dense cloud + mesh)	Brush (Gaussian optimization)
Refinement	Blender (UV mapping)	SuperSplat (Gaussian cleanup)
Output Format	FBX + PNG texture	PLY (Gaussians)

5. Results

5.1 3D scene reconstruction via 3DGS and photogrammetry

The reconstruction of the grand amphitheatre results in a dataset of 3,983 frames extracted at 3 fps from 22 minutes of video footage. Despite the presence of motion blur in several frames, both pipelines successfully generate complete 3D scene representations (Tab. 2). The sparse point cloud, used for both the photogrammetric and 3DGS pipeline, is illustrated in Fig. 3.

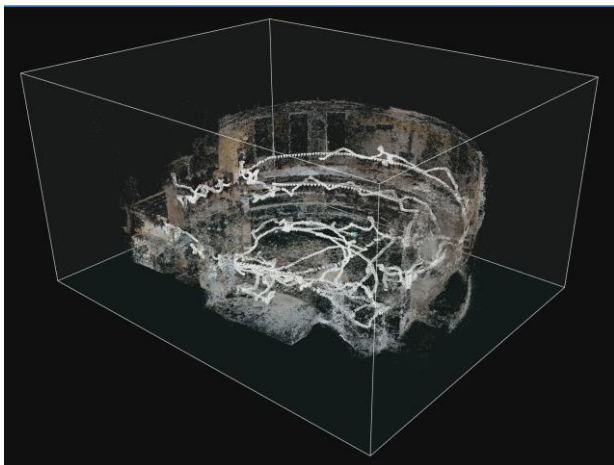


Fig. 3: Camera poses and sparse point cloud.

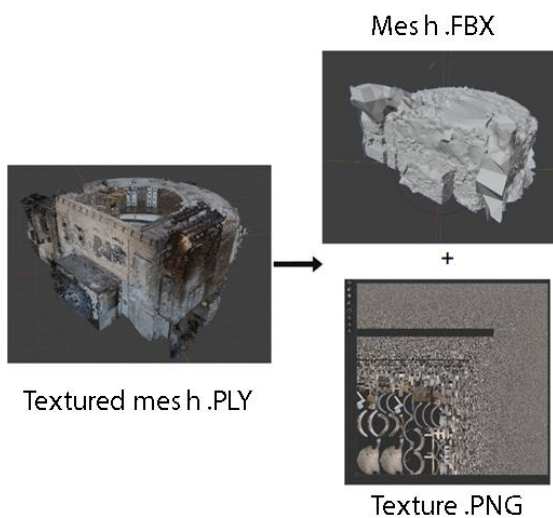


Fig. 4: Textured mesh of the amphitheatre interiors, obtained via Reality Scan.

Starting from this common baseline, the photogrammetric process produces a triangulated mesh through dense reconstruction and surface generation (Fig. 4); for the 3DGS approach, the sparse point cloud and the original images are imported into the Brush engine for the reconstruction of 3D Gaussians. An advantage of this approach lies in the possibility of monitoring the progressive refinement of the model during the training phase (Fig. 5), allowing intermediate visualization of the reconstruction before convergence. A subsequent cleaning step is performed using the SuperSplat editor to remove artefacts and outlier Gaussians.

Notable differences can be observed in computational performance and resource requirements. The 3DGS pipeline exhibits higher efficiency, completing the reconstruction with significantly lower memory and storage demands. In contrast, the photogrammetric workflow proves substantially more resource-intensive, requiring over 200 GB of page-file memory and approximately 250 GB of temporary storage during processing.

5.2 Experience set-up in Unity

The reconstructed models are imported to Unity to enable a direct comparison between rendering techniques and to set up the VR framework. Both models are spatially aligned based on control points of known distance acquired during data capture. Subsequently, spatial correspondence in terms of position, orientation, and scale is acquired by rotation-translation of the 3DGS model on the photogrammetric mesh (Fig. 6).

Navigation within the virtual environment relies on standard VR locomotion techniques and includes a teleportation system to facilitate movement between the ground floor and the upper level. In detail, the teleportation between floors is activated through spherical markers placed along the staircase, which serve as anchors for triggering the vertical transition.

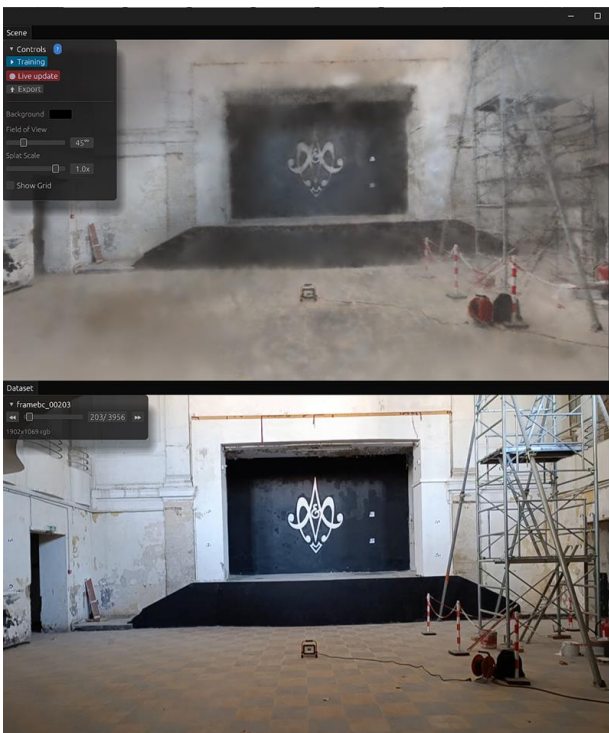


Fig. 5: 3DGS model at different training iterations.

The starting point for all users is positioned in front of the entrance door, on the ground floor (Fig. 7).

At the upper level, consisting of stepped platforms for gallery walkways, a specific solution is adopted to avoid discomfort during vertical displacement: a ramp-like visual effect simulates smooth elevation changes, further supporting navigation while moving across the stepped structure (Fig. 8).

A key feature of the application is the ability to switch between the 3DGS model and the textured mesh during the experience. At a predefined stage, users can trigger the transition by pressing the *A* button on the VR controller, which switches the active representation from the 3DGS model to the textured mesh while preserving the same viewpoint and environmental context.

This interaction design enables a direct perceptual comparison of visual quality, spatial coherence, and potential rendering artefacts between the two representations.

The adoption of a within-subject experimental design ensures that all participants experience both conditions under equivalent circumstances.

5.3 VR User Experience set-up and evaluation framework

The VR user experience is intended to assess the perceptual differences between

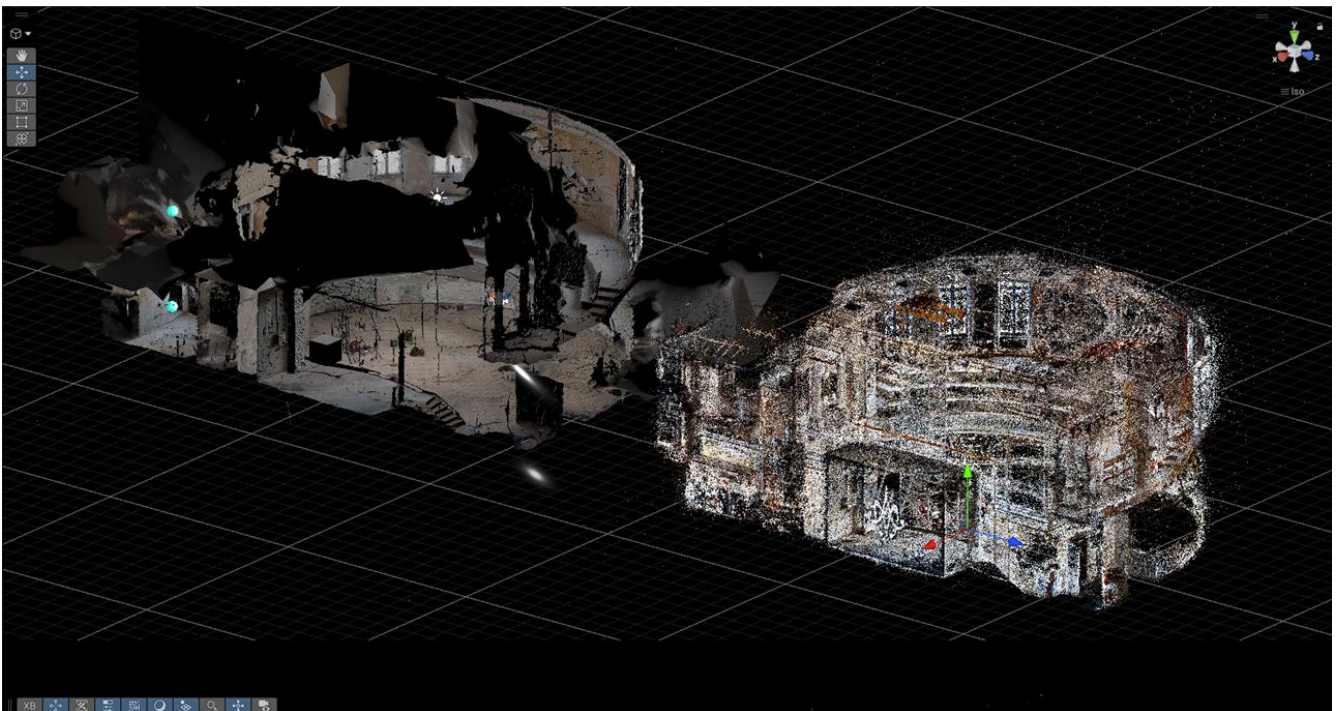
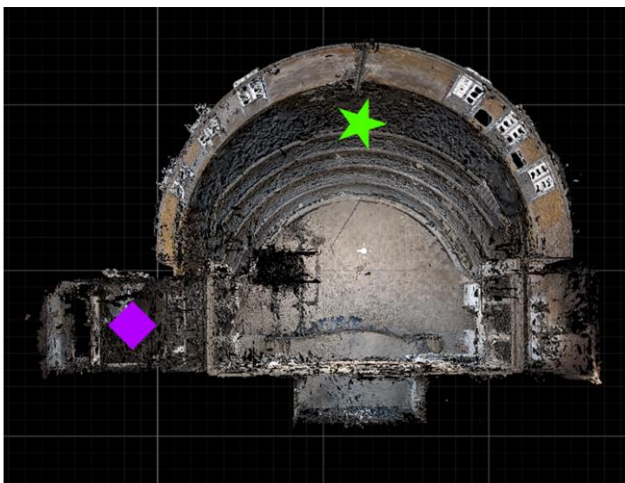


Fig. 6: Mesh (left) and 3DGS model (right) imported into Unity. For visualization purposes, the two representations are shown with a slight spatial offset, although in the final application environment they appear superposed.

photogrammetry-based and 3DGS representations during immersive exploration.



- ★ Starting point at the ground floor
- ◆ Teleport element: spherical markers located in front of the staircase to ensure a smooth transition from the ground floor to the upper level

Fig. 7: Starting point and teleport elements for the experience set-up in Unity.

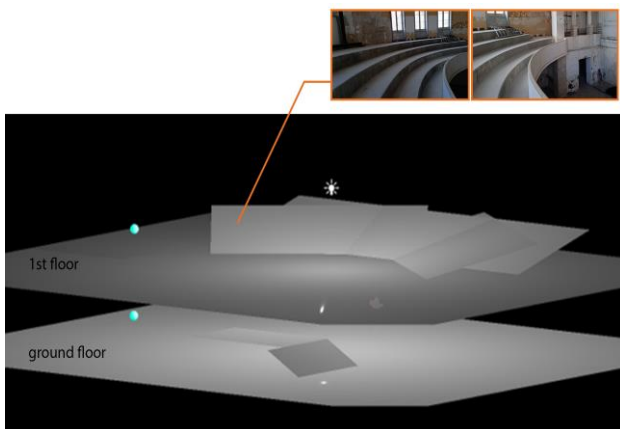


Fig. 8: Collision elements and teleportation points for the experience set-up in Unity.



Fig. 9: Scene from the user study and experimental phase: a participant wearing the VR headset and handheld controllers while interacting with the virtual environment.

In total, 20 participants are asked to navigate the virtual amphitheatre using a head-mounted display and standard VR motion controllers (Fig. 9, Fig. 10).

The experimental session follows a standardized protocol:

- Introduction and Briefing (5 minutes): Participants are welcomed and provided with a concise explanation of the study’s objectives, the experimental context, and the tasks they would be asked to perform;
- VR Tutorial (3-5 minutes): Participants are introduced to the VR system in a neutral training environment, where they practice locomotion, teleportation, and basic interaction.
- First condition experience (5-7 minutes): Participants explore the amphitheatre rendered with photogrammetry first. They are encouraged to examine details, move throughout space, and utilize the staircase teleportation to access the upper level.
- Model Transition: The system switches rendering techniques without repositioning the user, creating a direct perceptual comparison moment.
- Second Condition Experience (5-7 minutes): Participants continue exploring the amphitheatre interior with 3DGS; at this stage, they are also asked to switch between the two models at any time via the *A* button of the controller, for continuous back-and-forth comparison.
- Questionnaire Administration (10-15 minutes): After removing the VR headset, participants complete the evaluation questionnaire.
- Debriefing (5 minutes): Participants discuss their experience and provide qualitative feedback through open-ended questions.

5.4 Questionnaire results

The item-level questionnaire results for both photogrammetry and 3DGS conditions are presented in Fig. 11: for each of the 26 questionnaire items, the figure reports the mean participant rating together with the corresponding standard deviation.

Questionnaire items are grouped according to the six predefined constructs: Sense of Presence, Visual Fidelity and Realism, Lighting Shadows and



Fig. 10: Comparison between 3DGS and textured mesh for some scenes that users could explore.

Visual Consistency, Interactivity and Navigation, Technical Stability and Comfort, and Acceptance and Overall Perception.

In addition, paired participant scores for each questionnaire construct are obtained by averaging the questionnaire items belonging to the same construct; in Fig. 12, each line represents a single

participant and connects the scores assigned to the Photogrammetry and 3DGS conditions.

The mean item-level score differences between the two reconstruction methods, computed based on equation (1), are also reported in Figure 13 for each of the 26 questionnaire items.

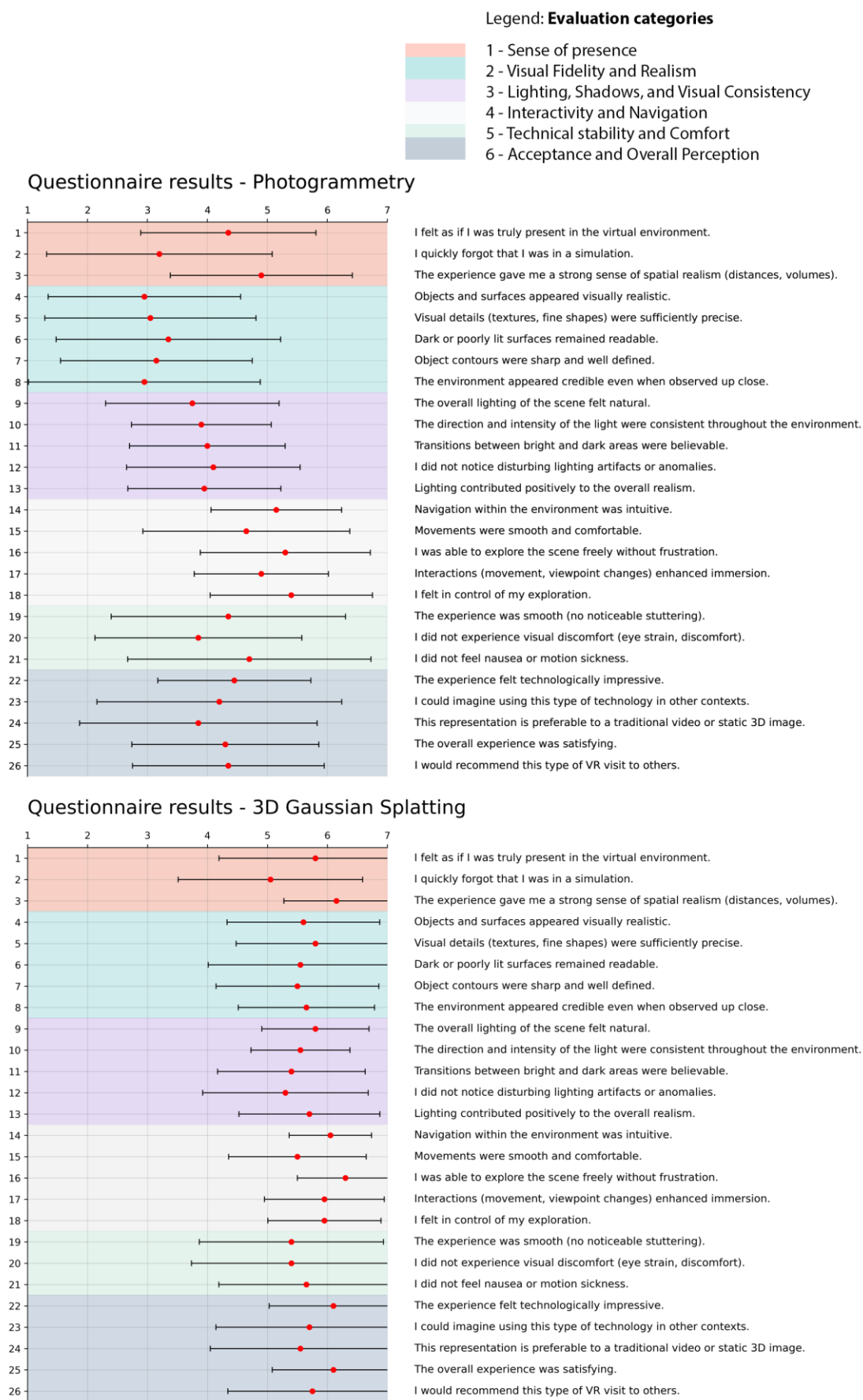


Fig. 11: Item-level comparison of questionnaire results for photogrammetry and 3D Gaussian Splatting (3DGS) across all evaluation categories (7-point Likert scale). Red markers indicate mean scores; horizontal bars represent response variability.

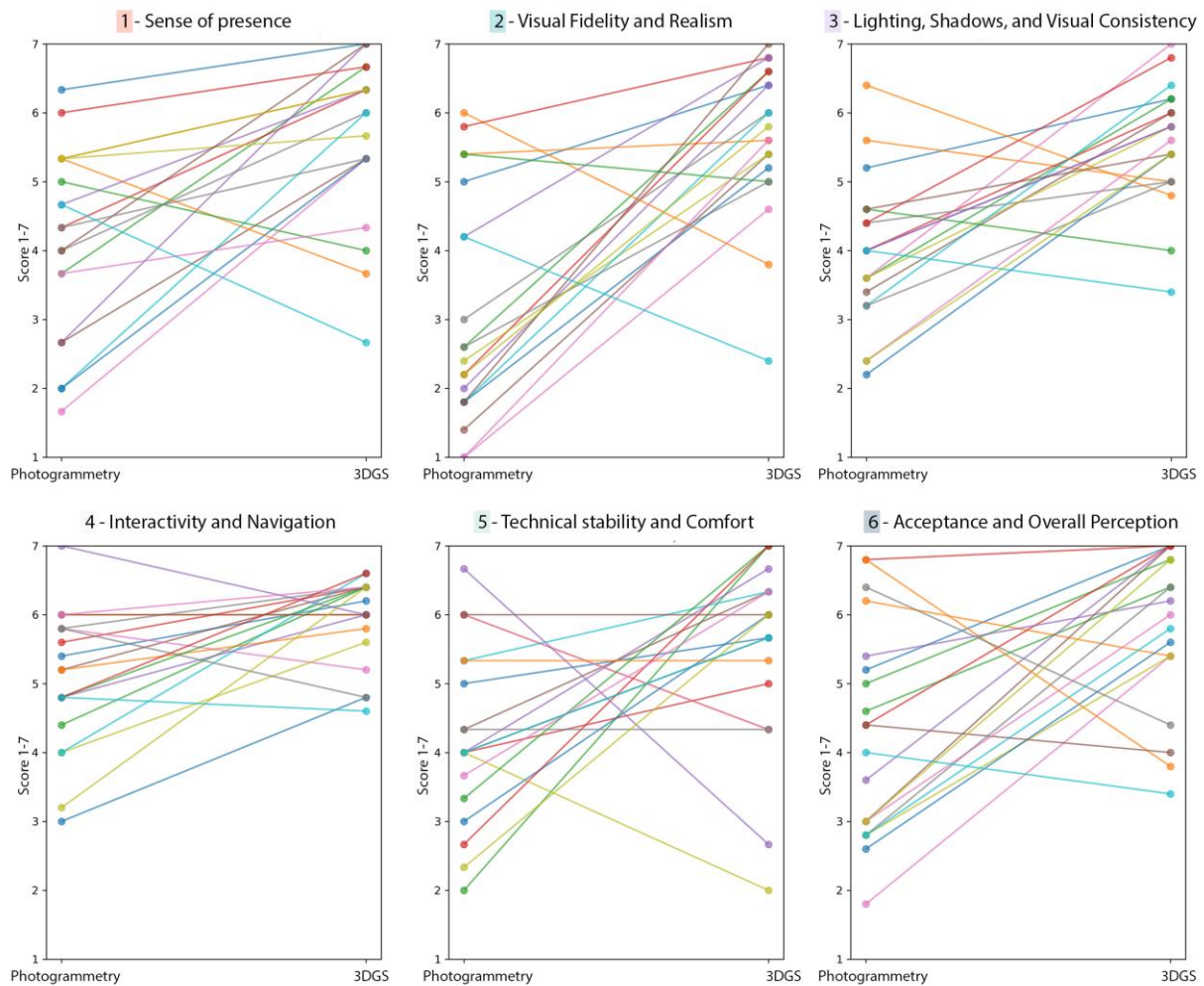


Fig. 12: Paired participant scores for each questionnaire construct (mean of corresponding items). Each line represents one participant, and construct scores correspond to the mean of the questionnaire items belonging to the same construct.

For a visualization of score distributions, central tendency, and variability across participants, Fig. 14 presents violin plots of construct scores for the two reconstruction methods.

Descriptive and inferential statistics for the six questionnaire constructs are finally reported in Table 3. Statistical comparisons were performed using the Wilcoxon signed-rank test, and the table reports the Wilcoxon statistic (W), the associated p -value, the rank-biserial correlation (r) as an effect size measure, and the Holm–Bonferroni corrected p -value.

6. Discussion

The questionnaire results reveal a consistent preference for the 3DGS model over the photogrammetric one when considering low-cost acquisition methods based on a smartphone device.

The violin plots of Fig. 14, in particular, show that the advantage of 3DGS is driven by an overall shift of the score distributions toward higher values (5 to 7). For almost all constructs, in fact:

- the median score is higher for 3DGS than for photogrammetry;
- the highest density of observations is concentrated between scores of 5 and 7;
- the 3DGS distributions generally extend less toward the lower end of the rating scale,

whereas the photogrammetry distributions still contain a substantial proportion of ratings between 1 and 4.

This pattern is particularly evident for *Visual fidelity and realism*; *Lighting, shadows and visual consistency*; *Acceptance and overall perception*.

Concerning *Interactivity and Navigation*, however, the two distributions exhibit a greater

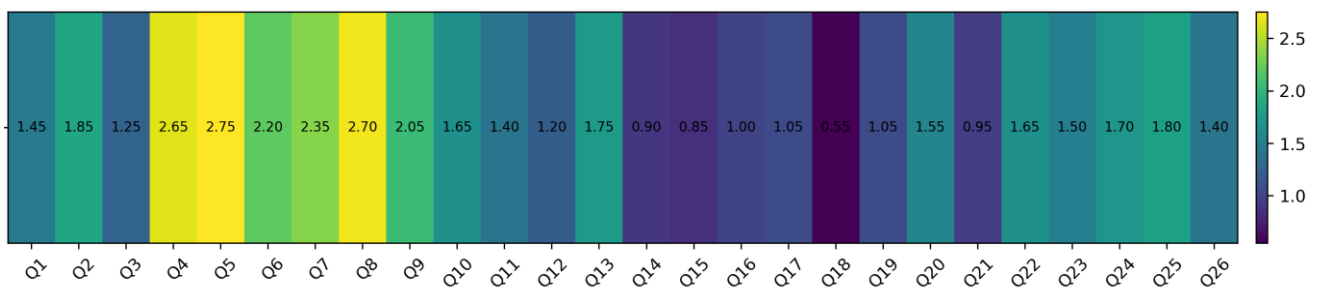


Fig. 13: Heatmap of mean item-level score differences ($\Delta = 3DGS - \text{Photogrammetry}$) across the 26 questionnaire items.

degree of overlap, indicating that the perceived differences for this construct are more limited than those observed for the visual-related dimensions.

Looking at the descriptive and inferential statistics of Tab. 3, the largest improvement was observed for the *Visual fidelity and realism* construct ($\Delta = 2.53$, $r = 0.8762$), suggesting that participants perceived the 3DGS reconstruction as more realistic than the photogrammetric model. This finding is consistent with the ability of Gaussian Splatting to preserve fine visual details, view-dependent appearance effects, and smooth rendering transitions, which contribute to a more convincing representation of the environment. The heatmap of item-level differences (Fig. 13) further confirms this observation.

Significant improvements were also found in *Lighting, shadows and visual consistency* ($\Delta = 1.61$, $r = 0.8571$). Photogrammetric reconstructions may exhibit lighting inconsistencies, texture baking artifacts, or reduced visual coherence under viewpoint changes. In contrast, the 3DGS representation appears to provide a more visually coherent reconstruction, resulting in higher ratings for illumination quality and scene consistency.

The increase observed for *Sense of presence* ($\Delta = 1.52$, $r = 0.7190$) suggests that the enhanced visual realism of 3DGS translated into a stronger feeling of being present within the virtual environment. Presence is known to be strongly influenced by visual fidelity, and the paired participant plots (Fig. 12) show that this improvement was consistent across most users rather than being driven by a limited number of participants.

Smaller differences were observed for *Interactivity and navigation* ($\Delta = 0.87$, $r = 0.7485$). This can be ascribed to the fact that navigation mechanics, locomotion, and interaction paradigms were identical across both conditions, therefore

the reconstruction method primarily influenced visual perception rather than the interaction model itself. Nevertheless, participants still reported slightly higher scores for 3DGS, suggesting that improved visual feedback may indirectly contribute to a more effective exploration experience.

The *Technical stability and comfort* construct exhibited the smallest effect size ($\Delta = 1.18$, $r = 0.5490$), so demonstrating that comfort and perceived stability do not specifically depend on the reconstruction technique but rather on factors such as frame rate, headset characteristics, and locomotion design.

Finally, *Acceptance and overall perception* showed a substantial improvement ($\Delta = 1.61$, $r = 0.6905$). The corresponding questionnaire items addressed overall satisfaction, perceived technological value, preference over traditional visual media, and willingness to recommend the experience.

The strongest gains were hence observed in dimensions directly related to visual realism and scene appearance, while more modest improvements were found for aspects less directly dependent on the reconstruction technique, such as navigation and comfort. This pattern is consistent with the expected characteristics of both reconstruction approaches and supports the use of 3DGS for immersive virtual reality applications where visual fidelity and user experience are critical factors.

Finally, as shown in the radar chart of Fig. 15, 3DGS achieves higher mean scores across all categories, with particularly pronounced differences in visual fidelity and realism (5.5 vs. 3.0) and lighting, shadows and visual consistency (5.5 vs. 4.0). Indeed, initial visual inspection revealed that while 3DGS successfully filled complex areas, it introduced a slight overall blur. Conversely, the photogrammetric mesh exhibited

Tab. 3: Descriptive and inferential statistics for the six questionnaire constructs.

Construct	Photogrammetry		3DGS		Δ	W (Wilcoxon)	p-value (Wilcoxon)	Rank biserial r	p-value (Holm-Bonferroni)
	Mean	SD	Mean	SD					
Sense of presence	4.15	1.366	5.67	1.199	+ 1.52	29.50	0.0032	0.7190	0.0126
Visual fidelity and realism	3.09	1.669	5.62	1.122	+ 2.53	13.00	0.0002	0.8762	0.0010
Lighting shadows and visual consistency	3.94	1.057	5.55	0.870	+ 1.61	15.00	0.0003	0.8571	0.0013
Interactivity and navigation	5.08	1.004	5.95	0.629	+ 0.87	21.50	0.0053	0.7485	0.0146
Technical stability and comfort	4.3	1.302	5.48	1.370	+ 1.18	34.50	0.0464	0.5490	0.0464
Acceptance and overall perception	4.23	1.532	5.84	1.160	+ 1.61	32.50	0.0049	0.6905	0.0146

significant "holes" and artifacts in areas with low texture density.

These results indicate that users perceived the 3DGS representation as significantly more realistic and visually coherent, a consideration that can be attributed to the ability of 3DGS to produce a continuous radiance-based representation, which mitigates common artefacts observed in photogrammetric reconstructions as geometric discontinuities, surface holes, and texture inconsistencies.

Smaller differences are rather observed in interactivity and navigation (5.5 vs. 5.0) and technical stability and comfort (5.5 vs. 4.3), suggesting that such aspects are less dependent on the reconstruction technique and more influenced by the shared VR implementation.

Nevertheless, the slightly higher score of 3DGS in comfort-related metrics may reflect the reduced presence of disruptive visual artefacts.

Despite the overall preference for 3DGS, certain limitations remain: while photogrammetry

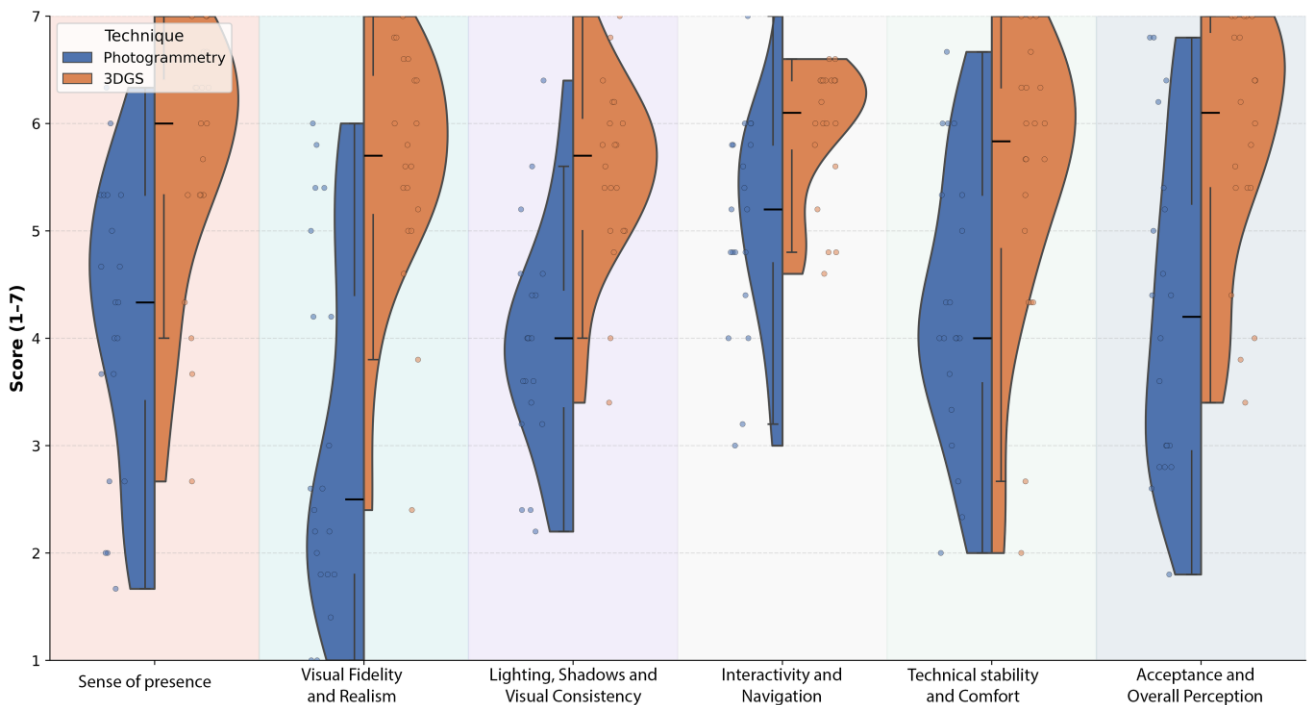


Fig. 14: Violin plots of construct scores (mean of the questionnaire items belonging to the same construct) for Photogrammetry and 3DGS across all participants.

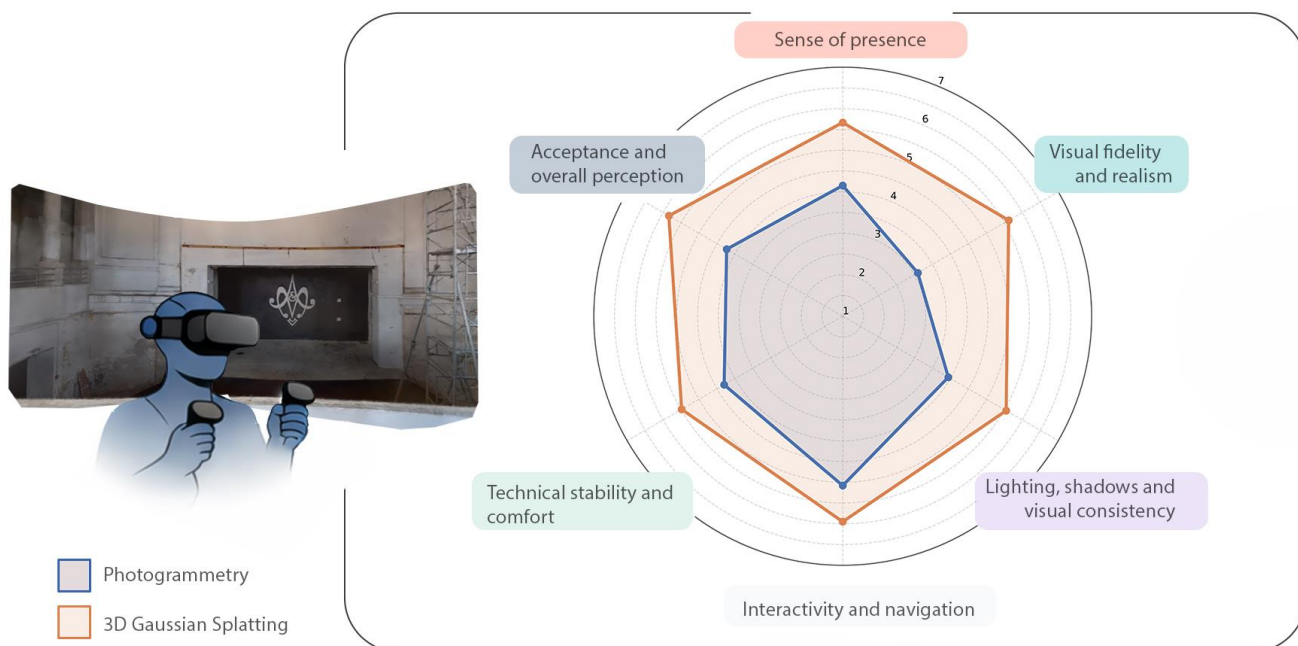


Fig. 15: Radar chart comparing the mean user experience scores for photogrammetry and 3DGS across evaluation dimensions (7-point Likert scale). Values represent the average scores computed for each category.

provides explicit geometric detail, 3DGS may introduce localized blurring in fine structures.

However, participants generally perceived these artefacts as less detrimental than the geometric inconsistencies present in mesh-based reconstructions derived from low-cost data.

7. Conclusion

This study presented a user-centered comparison between photogrammetry and 3DGS within an immersive VR environment, using low-cost smartphone acquisition and ensuring identical input data and evaluation conditions. The work contributes to a deeper understanding of data-driven 3D representations in immersive environments and lays the groundwork for future investigations aimed at bridging the gap between accessible acquisition methods and high-quality VR experiences.

The results indicate a consistent preference for 3DGS across all assessed dimensions, particularly regarding visual fidelity, lighting realism, and overall perceptual quality.

Compared to photogrammetry, 3DGS delivered a more coherent and immersive visual experience, effectively reducing artefacts typically associated with reconstructions derived from low-cost imagery.

Despite its limitations in fine-detail sharpness, 3DGS proved more robust to acquisition imperfections and more efficient in terms of computational resources. Both approaches, however, showed comparable performance in interaction, navigation, and user comfort, suggesting that these aspects depend primarily on VR system design rather than on the underlying 3D representation.

Future work will explore user experience across datasets of varying quality, including higher-fidelity acquisition systems, to better understand how input data characteristics influence reconstruction performance or user perception.

8. Author contributions

Conceptualization, V.C., P.V.; Methodology, V.C.; Validation, V.C., A.U.; Formal Analysis, A.U.; Investigation, V.C., A.U.; Data Curation, A.U., V.C.; Writing – Original Draft Preparation, A.U. V.C.; Writing – Review & Editing, V.C, P.V.; Visualization, V.C., A.U.; Supervision, V.C, P.V..

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