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Virtual Reality applications for visualization of 6000-year-old Neolithic graves from Lenzburg (Switzerland)

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A B S T R A C T

The last decade has seen a steady increase in the application of virtual 3D approaches in cultural heritage research. Although a large literature exists about the advantages of 3D methods in this field, here we go one step further and elucidate a) how image-based 3D reconstructions can be displayed in virtual reality (VR) space using freeware game engine software and low-cost VR hardware and b) highlight the relative benefits and advantages with a focus on interactive museum displays of relatively large archaeological objects. Specifically, we present three 3D models of different stone grave structures from the Neolithic necropolis of Lenzburg (Northern Switzerland, 4450-3500 BCE). The site has been excavated in 1959/60 and certain graves were subsequently preserved for museum display. By means of VR applications, it is now possible to experience these approximately 6000-year-old tombs with an innovative approach circumventing various barriers or constraints and offering interactive display options.

1. Introduction

1.1. Aim of the study

Our aim in this paper is to demonstrate how photogrammetric 3D reconstructions of larger archaeological objects can be created and displayed in virtual reality space using low cost hardware and software. While other publications cover specific aspects of similar methodology (e.g. Gonizzi Barsanti et al., 2015; Bruno et al., 2010), we focus on conceptualization and implementation with novel interactive display options for users. As the Neolithic grave structures from Lenzburg have been excavated and documented in the 1960s, this paper does not cover the application of 3D techniques for *in situ* documentation (e.g. Siebke et al., 2018; Forte et al., 2012). Rather, our aim is to explore the advantages and new possibilities offered by virtual reality applications to further enhance the experience of larger museum objects with an approach that is applicable and suitable for various contexts. We consider this a valuable contribution, as our outlined method significantly improves accessibility, while circumventing several barriers, as the size of the original objects, lack of space and fragile state of preservation or conservation requirements often prevents similar cultural heritage to be transported and exhibited to a broader audience.

1.2. Archaeological context

The Neolithic necropolis of Lenzburg (canton of Aargau, Switzerland, Fig. 1A) was discovered in 1959 during construction works between the two hills of the Schlossberg and the Goffersberg east to the city of Lenzburg. In 1960 parts of the necropolis were excavated in multiple short campaigns, conducted by the Swiss National Museum. This led to the discovery of 16 stone cist graves and of a larger, more complex funerary structure of almost megalithic character (Fig. 1B). At least four lateral stone slabs of small dimensions (length less than 1.25 m) formed the stone cist graves. The larger structure consisted of stacked stone slabs forming several small chambers, and was given the label "funerary monument" (with the running number 2). In the Western

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Alpine region, stone cist graves similar to those found at Lenzburg are referred as of the "Chamblandes" type. The latter with necropolises of well over 100 graves around Lake Geneva or clusters of sites in the Upper Rhône Valley (Switzerland) and in the Aosta valley (Italy), mostly dating to the second half of the 5th millennium BCE (Steuri et al., 2023; Denaire et al., 2011; Gallay 2008; Jeunesse et al., 2019; Stöckli 2016). Radiocarbon dating of human bone samples situates the individual stone cist graves of Lenzburg between 4450 and 4050 BCE, while the burials of the complex funerary monument seem to be at least 400 years younger, dating to ca. 3950–3500 BCE (De Capitani 2007).

Funerary practices tend to vary at the site, with the co-presence of graves used only once and collective structures including up to 17 individuals and pertaining to different usage phases. Within the stone cist graves, buried individuals were generally placed hyperflexed on their left side. Although the majority of burials consists of primary inhumations, other practices can also be observed. These include secondary treatments, like the re-arrangement or retrieval of skeletal remains and, sporadically, cremations (Wyss 1998, regarding used terminology, see Knüsel 2014; Duday 2009; Duday 2006).

1.3. Grave structures as museum objects

In spring 1960, unfavorable research conditions and time constraints prompted the archaeologists to block-lift the Neolithic grave structures from Lenzburg. These were then transported to the Swiss National Museum in Zurich for further examination. In the field, a coat of plaster was applied to protect and stabilize the often weathered and brittle lateral stone slabs. Afterward, wooden casings were built around each grave to allow lifting the whole blocks by crane (Fig. 2A and B). The block lifting of the large funerary monument, weighing about 30 tons, required more than three weeks of preparation and two crane trucks (Fig. 2C and D; Wyss 1998).

At the Swiss National Museum each grave structure was disassembled and documented layer by layer (Fig. 3). Some stone cists and their included skeletal remains were left relatively untouched to preserve their anatomical connection and targeted for exhibition purposes. Skeletal remains were however cleaned of superficial soil and, together with the underlying sediment, hardened with binding agents (Wyss 1967, 1998). The grave structures were exhibited in the Swiss National Museum from 1985 to 2009. They were then gradually transferred to the warehouse of the archaeology department of the canton of Aargau in Brugg and the Museum Burghalde in Lenzburg. Visitors can nowadays view the funerary monument and two cist graves in the latter's permanent exhibition.

1.4. Principles and applications of image-based 3D reconstructions in archaeology

To reconstruct a three-dimensional object from two-dimensional photographs, structure from motion (SfM) software semi-automatically identifies common features on overlapping photographs and tracks their positions. From the partially known geometries of the camera as well as the lens, the resulting photos and the measured distances, the positions of the observed features are obtained as a point cloud in a metric 3D object space according to the principle of parallax. At the same time, the three-dimensional camera positions and their orientation are also computed, which then form the basis for densifying the point cloud using stereo matching and ray intersection. These computed three-dimensional point clouds then serve as a framework for further processing into textured meshes, elevation models, or orthophoto mosaics (Reich et al., 2021; Luhmann et al., 2020; Szeliski 2011).

In archaeological research, image-based 3D reconstructions in the form of SfM models have become regularly integrated in various forms to document and visualize cultural heritage (e.g. De Reu et al., 2014; De Reu et al., 2013; Green et al., 2014; Verhoeven 2011; Verhoeven et al., 2012). The wide adoption of photogrammetry is mainly due to it being relatively inexpensive, with no need of special set ups, and easy to use (Strasser et al., 2018).

Virtual Reality applications allow users to interact with 3D models and become agents in a virtual environment. These techniques have been employed in archaeology and cultural heritage since the 1990s (Bruno et al., 2010). Virtual Reality offers the advantage of making cultural heritage digitally accessible, which becomes especially important when physical access is constrained (Kyrlitsias et al., 2020; Bekele et al., 2018; Knabb et al., 2014). Furthermore, since they offer the opportunity to visualize an archaeological excavation in virtual reality (Forte et al., 2012), virtual methods may be particularly useful for research, education, and valorization purposes. But virtual archaeology has also introduced experimental elements going beyond traditional visualization of 3D models giving users agency in witnessing and learning about the past (Pujol-Tost 2019). In recent years there has been a continuous development of new methodologies for the application of immersive virtual reality-mediated experiences specifically for the context of Digital Archaeology (Brooks 2019; Pujol-Tost 2017). For example, with the novel theoretical framework of Cultural Presence to investigate if and how current virtual environments achieve the feeling of traveling to the past (Pujol-Tost 2019).

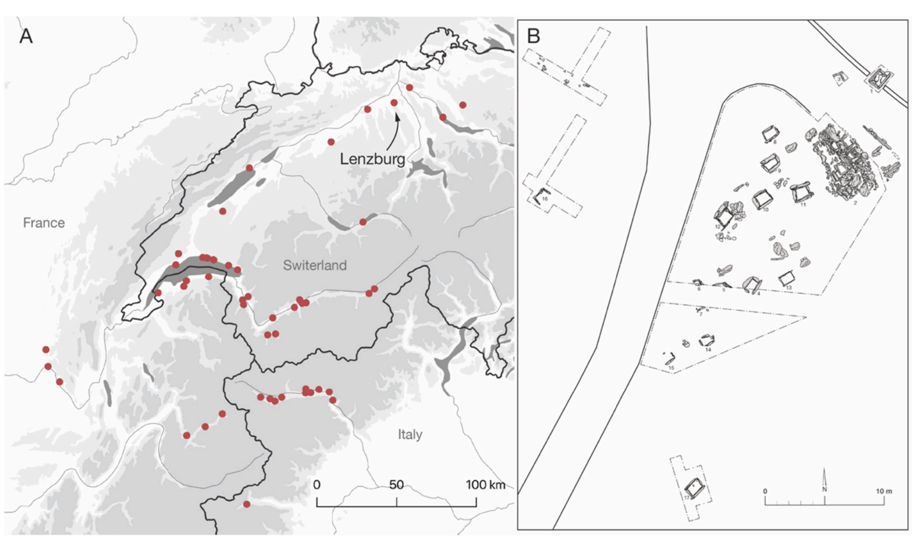

Fig. 1. A) Distribution of contexts with Neolithic cist graves in the Western Alps and B) map of the necropolis of Lenzburg, Goffersberg (based on Wyss 1998).

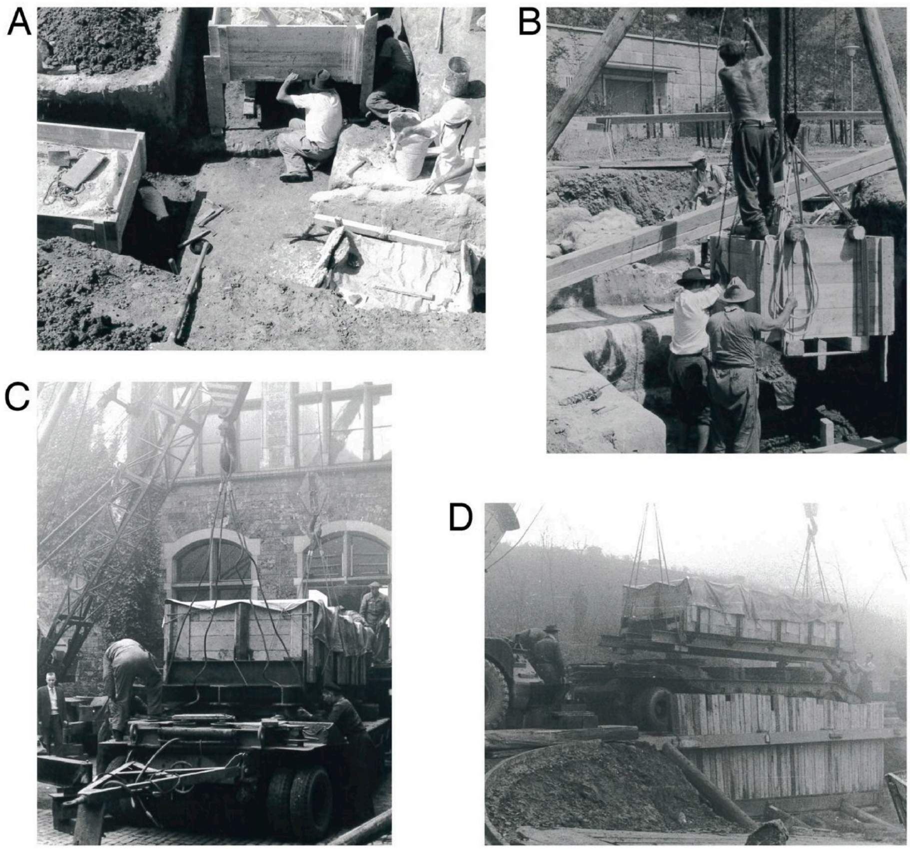

Fig. 2. A) and B) blocks lifting of the stone cist graves, C) and D) block lifting of the funerary monument by two crane trucks (Photos: Wyss 1998).

Fig. 3. Dissection of the recovered grave structures in the laboratory of the Swiss National Museum in Zurich (Photos: Swiss National Museum).

2. Material and methods

The Neolithic grave structures from the Lenzburg necropolis included in this study (Graves 9, 12, and the Funerary Monument) were selected according to their logistical accessibility, suitability for a full photogrammetric study, and archaeological features representing different funerary practices at the site:

- *Grave 9* is a collective burial of at least 11 individuals including different age classes and both sexes. The commingling of skeletal elements suggests distinct phases of use and the performance of both primary and secondary burials. The structure measures 1.15 by 0.95 m, and the four lateral stone slabs were preserved in-situ.
- *Grave 12* is the burial of an adult male provided with a relatively large number of grave goods. This grave is remarkable since it is the largest (1.25 by 1.05m) stone cist in the necropolis and includes the only single burial found at the site. In this case, the lateral stone slabs are no longer present (Fig. 4).
- The *funerary monument* is a complex structure composed by stacked stone slabs overall measuring approx. 4.7 m of length and 3.3 m of width. It consists of small, partially interconnected chambers (50–60 cm long and 30–40 cm wide). The individual chambers generally contained only few human remains of subadult individuals or were empty at the time of discovery.

There follows a detailed description of the protocol used to obtain

Fig. 4. Photographic recording of grave 12.

the 3D model and its implementation in VR. We will focus on the application for the funerary monument, as we followed the same method for the smaller graves 9 and 12.

2.1. Image-based 3D reconstruction

For the photographic recording, the funerary monument was accessible from all sides horizontally, as well as partially overhead via a walkway on the upper floor of the museum. We took the photographs with a Canon EOS 5D Mark III and a Canon EF 24–70 mm f/2.8L II USM lens fixed to the focal length of 24 mm. Due to the absence of natural light in the Museum room, the scene had to be artificially illuminated. To this aim, we used three construction site spotlights and a Canon Speedlite 470 EX-AI flash head. Under the less than ideal lighting conditions in the dark showroom, the camera parameters chosen represented an attempt to find an optimal compromise between image quality and depth of field with the greatest possible consistency across the entire series of images. The 654 photos used were all shot handheld with fixed parameters at f/8, shutter speed 1/80 and ISO 250. The goal was to photograph the funerary monument from all accessible directions and achieve an overlap of about 80% between each photo. For accuracy and the subsequent scaling of the 3D model, four pairs of coded markers were placed around the object and the distance of each pair was measured (Fig. 5).

For the reconstruction, we used the commercially available software Metashape Professional (Agisoft LLC, 2021). The small chambers within the funerary monuments are covered with acrylic glass to protect the human remains from dust and litter, which could not be removed. This resulted in distracting light reflections that we manually masked before reconstruction. After the initial alignment of the photos, we filtered the point cloud and optimized the camera positions accordingly. Based on confidence values we further filtered and manually cleaned the subsequently calculated dense point cloud. We then manually cropped this first mesh to the funerary monument's extent, masking everything except the monument itself in all photos. We achieved the following accuracy values, which can be deemed as good according to Over et al., 2021: Total reprojection error of 0.229 pixel, residual error vectors of less than 1 pixel and a total scale bar error of 0.0377 cm.

To simplify further processing, we reduced the mesh using the "Decimate Mesh" tool in Metashape Professional from the original nearly 10 million faces to 500'000 faces (as advised by the hardware manufacturer, see below) and finally provided it with a texture. We then exported the three-dimensionally reconstructed funerary monument in a wavefront OBJ format together with its texture for further processing.

2.2. Implementation in VR

We decided on the headset Meta Quest 2 (Oculus Inc.) for a stand-alone virtual reality hardware, as is was deemed cost effective, user friendly and offering a good development environment. However, even if reduced to 500'000 polygonal triangles, the mesh still exceeded the upper bound limit, accordingly, we further reduced the wavefront file in the open-source software Blender 3.0 (Blender Online Community, 2021). With the simple collapse function applied as a modifier on the mesh, we discarded unnecessary information (e.g. vertices that lie on a connecting edge between two other vertices) to allow for real-time lighting of the scene and shadow calculation. This step allowed to reduce the mesh to 200'000 triangles. Having real-time shadows, albeit expensive in terms of compute power, strengthens believability and object recognition in the virtual environment (Welty and Setiawan 2019; Berkman and Akan 2019). We used the game engine Unity (Unity Technologies, 2022) as it offers all functionality necessary to build a virtual environment that can be accessed by virtual reality headsets. Unity is freely accessible and allows implementations of additional packages by third parties. The oculus-integration is a template to build virtual reality applications with the necessary components like stereoscopic rendering (producing one image per eye per frame to emulate depth in the virtual environment) and the positional and rotational tracking of the camera (Fig. 6).

The limitations of the target hardware, a standalone virtual reality headset, and the texture of the pre-existing mesh were not sufficient in

Fig. 5. A) Top view of the funerary monument via the walkway on the upper floor of the Museum Burghalde Lenzburg, B) Point cloud reconstruction and individual camera angles of the funerary monument displayed in Metashape Professional (Agisoft LLC, 2021).

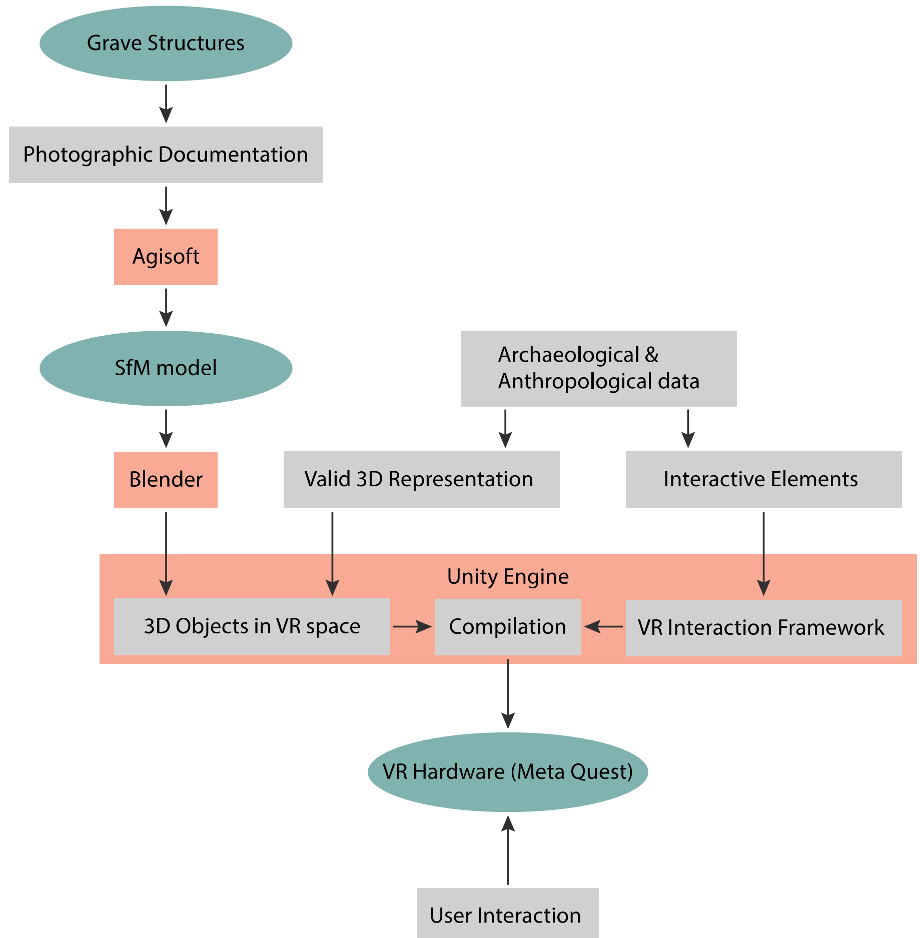

Fig. 6. Flowchart depicting the steps from image-based reconstruction (SfM) to VR application of the grave structures.

creating the detail necessary in the virtual environment. Our mesh has a surface area of 301'344.5 cm^2 and we have 16 million pixels of color data from the texture. To create a credible simulation and increase the perceived texel-density (pixel per unit of measure in a mesh) for the observer, a secondary texture is overlaid recreating a finer detail level. This texture is a seamless color-noise that was multiplied fifty by fifty times over the existing texture. This strengthens the sense of presence in the final application (Jung and Lindeman 2021).

Both textures are filtered trilinear without using anisotropic filtering (anisotropic filtering refers to a method of sampling a texture on a mesh surface that lies oblique towards the camera angle to reduce smear produced by oversampling a large texture that is very slim due to its oblique angle) as the mesh is small enough to avoid smearing effects (Weickert 1998). The scene setup in unity consists of the player-logic from a virtual reality integration package, a flat plane on which the funerary monument mesh is placed, and a point light which is attached to the left hand of the tracked controller. Attaching the light-source to the controller allows for the light source to be moved and with that giving the observer agency beyond simple movement in the virtual environment. Of the pre-eminent movement in virtual reality applications natural movement and the functionality to teleport were added as they are the least prone to create nausea or cyber-sickness (Boletsis and Cedergren 2019). The background appears black and fading into distance (Figs. 7–9), since it is intended to later display the actual exhibition room of the museum. Using the so-called Passthrough camera feed specific to Meta Quest 2 (Oculus Inc.), this mixed reality approach gives the observer a real-time view of their surroundings, aiding in safety and lessening the sense of isolation.

To add interactive elements, we used the VR Interaction Framework software package (Bearded Ninja Games 2022) available in the Unity Asset Store. Among many alternatives, this framework lends itself to novice developers in VR, offering basic interaction functions in the virtual environment and allowing to easily create grabbable objects that can be moved (in our case grave goods or capstones of the stone cists).

More complex interactive elements needed to be programmed in code. This was the case for the simulated, removable sediment covering the funerary monument. The used digital shovel was created from a template provided by the Framework software package. Within the Unity engine, tags were assigned to this shovel to create a program that checks collisions of the shovel with the simulated sediment. This allowed to set up an interaction system where every collision of the shovel with the sediment scaled down the latter, creating an effect of the sediment being shoveled off.

The data of the 3D models with all non-proprietary software will be stored on the GitLab open source repository of the Zurich University of the Arts, while the android application package (APK) for the VR content will be freely available at the SideQuest platform. This will allow direct downloads to stand-alone virtual reality hardware (e.g. Meta Quest 2), providing remote access to the broader public.

3. Results and discussion

The resulting models can be experienced using most common VR headsets and control schemes as the VR Experience can be compiled for different platforms from the Unity Engine and the used Unity Software Packages. The headset offers a first-person stereoscopic view and the ability to physically change the direction of view with head movements. The handheld controllers allow the users to navigate through the VR space and interact with the models. Interactive points within the VR space are visualized by bright colored frames contrasting the dark background and different textures. Research and experiences of recent expositions shows that users intuitively understand the use and application of these gadgets moving through the virtual environment (Doukianou et al., 2020; Gonizzi Barsanti et al., 2015). Credible reconstructions and high-resolution visual presentations that the user can interact with are a major aspect in the immersive aspect of VR models, resulting in a higher level of presence and an overall positive experience for users (Jung and Lindeman, 2021; Kyrlitsias et al., 2020). However, it is important to consider that the virtual site represents not an objective reality, since it is rather a representation of a perceived past reality that is informed by the creators' theoretical positions and cultural sensitivities (Knabb et al., 2014).

3.1. Improved accessibility

One major advantage of 3D applications in cultural heritage is an improved accessibility. Larger objects, which previously could not be displayed in museums or expositions due to spatial constraints, transportation difficulties, and other conservation concerns or deficits (humidity, temperature etc.) can now be shown digitally to visitors, as we are able to demonstrate with three examples:

- In 2020, the Cantonal Museum of Prehistory in Zug (Switzerland) intended to display the original grave structure of Grave 9 in a temporary exhibition. This turned out to be impossible due to spatial constraints. The structure was indeed too large to fit through the museum's doors. As an easily integrated alternative, visitors were able to view and interact with the first versions of our 3D model of Grave 9 on a tablet (from November 2020 to May 2021).
- Due to similar spatial constraints, it was so far not possible to display Grave 12 in the Museum Burghalde (Switzerland). However, being the only single burial with a relatively large number of grave goods, this object is of major importance for the understanding of the whole necropolis. Therefore, our interactive 3D model of Grave 12 will be displayed via a stationary VR headset in the museum (starting autumn 2023).
- Currently, a physical information board with basic facts about the Neolithic necropolis indicates the original location of the discovery of these graves. In the future, a QR code will be imprinted on this board, directly linking to the 3D models, giving the public the opportunity to view these graves in their original environment (presumed they have mobile internet access). This will further highlight the improved accessibility and new ways of displaying these 3D models offer.

3.2. Interactive display options

Considering that users generally tend to engage with immersive content for longer periods of time (Doukianou et al., 2020), we implemented certain interactive elements in these grave models: For example, the missing capstone of the stone cist Grave 9 was virtually added, which can now be lifted in the VR space, giving users agency and engaging them in the virtual environment, enhancing the potential for immersion and presence (Fig. 7). Further, soil sediment was simulated, surrounding the funerary monument, giving viewers the opportunity to perform a simplified excavation using VR controllers and intuitive hand gestures (simulating shovel work; Fig. 8). In addition, the different grave goods of grave 12 are highlighted and interactive, allowing a detailed viewing of these objects (Fig. 9). If selected, short inputs appear informing the viewer on its function and use, as well as the place of origin of stone axes, flint arrowheads or animal bone tools. Similarly, the user can select specific human skeletal remains for which the system then provides a suite of anthropological information (e.g. age, sex, or presence of pathologies).

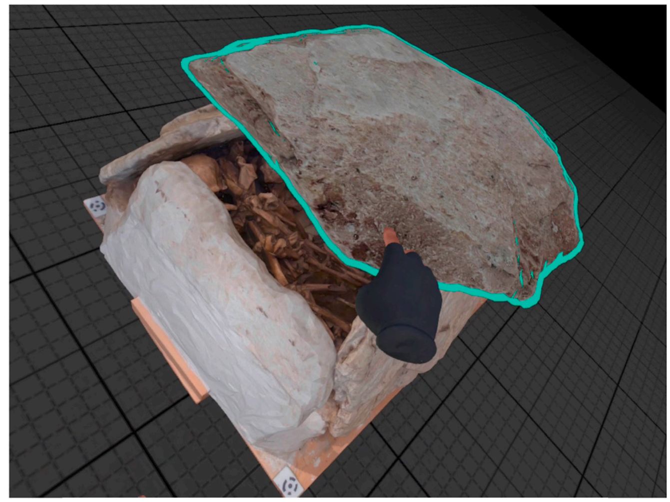

Fig. 7. Simulated, movable capstone over the stone cist grave 9 (recorded from Meta Quest 2).

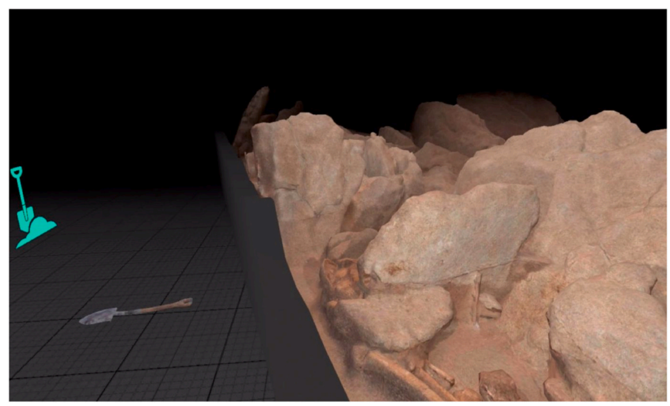

Fig. 8. Removal of artificial sediment around the funerary monument using hand gestures simulating shovel work (recorded from Meta Quest 2).

Fig. 9. Interactive grave goods and floating information board of the published anthropological data (Wyss 1998) regarding Grave 12 (recorded from Meta Quest 2).

3.3. Future steps to enhance the interactive experience

The possibility to imbed further information for viewers offers a multitude of new display and presentation options, further demonstrating the unique potential offered by VR applications. In that sense, first steps have been taken to animate a virtual human using motion capture technology using the system of the Immersive Arts Space at the Zurich University of the Arts (Furtado et al., 2018). The idea is that at specific waypoints in the VR space (for example while looking at the human remains or grave goods) prerecorded inputs can be played, informing the viewer on excavation techniques or the way of life of the buried individuals (burial practices, diet, health status, crafting of tool or building of houses). These inputs are being developed in cooperation between museology and current archaeological knowledge. The animated person could be in the form of a museum guide, a “digital archaeologist”, or even of a “Neolithic” individual contemporary to the time of use of the necropolis. Planned implementation includes the grave structures into the surrounding natural landscape (using mostly modified, existing templates), additionally removing modern artificial structures in order to better depict the necropolis and the original topography of the region in the VR space. An acoustical environment like an ambient nature soundscape or movement-triggered footstep sounds delivered via noise-canceling headphones could additionally improve the feeling of presence and realism of this enhanced virtual model (Kern and Ellermeier, 2020).

4. Conclusion

Due to spatial, logistic, and/or economic constraints, it is often not possible to display large archaeological objects or structures in museum exhibitions. An increasingly adopted strategy to expand accessibility to these finds by the specialists and the general public are digital representations, which offer the additional advantage of an interaction between the user and the digital virtual models. For the first time, we provide a step-by-step demonstration of how 3D reconstructions of Neolithic funerary structures can be created and displayed in virtual reality space. This approach offers new interactive and immersive display options for the viewer. Further, our presented method is universally applicable and suitable for various contexts. We support these implementations to be incorporated in the conceptualization of future exhibitions, facilitating access to cultural heritage for the public.

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