EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2021)
A. Chalmers and V. Hulusic (Editors)

Interactive 3D Artefact Puzzles to Support Engagement Beyond the Museum Environment

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(a) *3D puzzle pieces for interactive digital online 3D puzzle activity.* **(b)** *Puzzle viewer with semi-transparent puzzle piece, loaded clue and partially assembled puzzle.*

Figure 1: *Digital 3D puzzle activity.*

Abstract

The need for online 3D interactive experiences was evidenced during the COVID-19 lockdowns, as audiences across the world have been unable to visit museums, physically interact with their collections on site or digitally interact with technologies and digital media situated within such settings. As a response, this research addresses gaps identified in a review of the digital offerings from UK and US museums during the 2020 lockdowns, highlighting the limited number and nature of 3D interactive offerings provided, despite the wide efforts on 3D digitisation over the last decade. Thus, the research investigates the development and testing of an online 3D interactive activity, resembling a physical activity situated in the archaeological gallery of Brighton Museum and Art Gallery (UK). Through a pilot user survey, the research aims to understand what is the impact of such online offerings to better contextualise heritage collections; enhance cultural heritage learning and appreciation; and complement physical activities of similar nature. The analysis of audiences' opinions about these interactions can be of great importance, as such activities have the power to enable active access to cultural heritage resources regardless of the physical location of users and transform heritage experiences in the long term. Our research indicates that, while the physical experience might offer advantages as far as it concerns the familiarity with the tactile nature of interaction, the digital counterpart has potential to allow for the experience of assembling the puzzle to achieve a wider reach.

CCS Concepts

• Applied computing $\rightarrow$ ***Arts and humanities; • Computing methodologies*** $\rightarrow$ ***Mesh geometry models; • Human-centered computing*** $\rightarrow$ *Empirical studies in interaction design;*

1. Introduction

Heritage organisations often seek more sustainable ways to care for and exhibit artefacts from their collections while enhancing the participation of audiences in the process of artefact interpretation. This interpretive process can help to illuminate the different contexts for the creation and function of artefacts, as well as their possible destruction or loss and their subsequent discovery by archaeologists.

In the last few years, the incorporation of digital games in gal-

DOI: 10.2312/gch.20211403

leries has been promoted by the research community and museum professionals. Such digital games, known to many as Serious Games, propose solutions where game-based virtual experiences are applied in nontraditional game contexts, such as in the cultural heritage domain, to provide fun but also educational benefits to the user [PS16]. Nevertheless, many of these experiences can change the dynamics of the visit, by isolating users from their group and disrupting their attention. The extension of digital games into physical gaming activities within the gallery developed through 3D digital fabrication technologies has also been explored [ESW20]. Due to their nature, physical or tactile games of 3D printed replicas of artefacts constitute a collaborative activity that promotes the interactive and social aspect of a museum visit, while often working as the "hook" to attract visitors' attention [CH15].

In museum and visitor research, it is acknowledged that audiences are different [Ree09]. Hence, they have various, often conflicting, requirements with regards to experiences that satisfy their needs, both inside and outside of the museum setting. These needs were further exacerbated by the COVID-19 pandemic, as audiences were forced to only have digital access to artefacts from collections, and the number of modalities to enable such access to heritage resources became severely restricted. Furthermore, even though in the last fifteen years we have witnessed many 3D digitisation efforts facilitated by the advancement of knowledge and ease of access to digitisation processes, mostly through widespread photogrammetry, our previous research [SEP20] demonstrated that 3D content museum offerings during the lockdown periods were very limited. For those museums which were able to build 3D datasets in the previous years, their offerings are still limited; targeting mostly users accessing content through 3D viewers with limited interactivity.

Hence, this research is motivated by the need to develop a deeper understanding of how 3D content can be repurposed for a variety of physical and digital experiences. At the same time, we wish to explore how digital activities that refer to physical activities within the museum perform and how they might complement artefact interpretation when physical access to the activity might not be possible, not only due to restrictions but also in terms of reaching wider audiences.

This research was designed to extend our previous research [ESW20] by proposing an online interactive digital 3D puzzle activity, which "replicates" or "transfers" on the web a physical hands-on activity that we have developed for the Brighton Museum and Art Gallery. To evaluate the activity, a survey was also launched to understand audiences' opinions about this type of interaction with museum artefacts, particularly under the recent and possible future museum closures, which prevent visitors from physically accessing hands-on activities in the museum environment. As such the research questions were:

- What is the impact of 3D online interactive activities aiming to bring cultural heritage artefacts and related activities "closer" to users?
- How do these 3D online interactive activities affect users' awareness, knowledge, interest, appreciation and attitudes towards heritage collections?
- What are the users' requirements for interactive 3D experiences of museum artefacts to better contextualise heritage collections and enhance learning and appreciation?

The contribution of the research is the development of a 3D interactive online puzzle activity of an Iron Age archaeological artefact, by deploying a parallel digital approach for its construction and texturing. Secondly, it contributes insight on how such experiences address user needs by conducting a pilot test of the activity to understand how it promotes cultural heritage understanding and engagement.

The paper is organised as follows: Section 2 presents related work relevant to web-based interactive 3D activities, including a brief review on the COVID-19 offerings in a sample of museums in the UK and the US for contextualising the research. Next, Section 3 presents the development of the interactive 3D digital puzzle activity including the creation of the 3D assets, interaction and data collection for user testing. Finally, Section 4 presents the preliminary evaluation of such system and conclusions are presented in Section 5.

2. Related work and COVID-19 perspective

Following the constructivist approach, suggesting that people, and particularly young audiences, engage, understand and learn more effectively when interacting with objects and available resources, cultural heritage organisations have incorporated interactive activities both within their on-site and online offerings to their audiences [FD13]. Such activities are popular with families and school pupils, which are amongst the strongest visiting groups in UK museums [The18], but also with adults who desire a more interactive experience of cultural heritage.

Such desire, intensified by physical movement restrictions and museum closures during the pandemic, highlighted the importance of enabling interactive heritage experiences beyond the museum environment. Building on previous research [SEP20] to understand the types of access that heritage institutions have made easily available to their audiences during the pandemic, particularly through web technologies, we investigated a variety of 3D related content. This includes 360° tours, Virtual and Augmented Reality applications and 3D models of heritage objects.

A comparative assessment of the digital offerings amongst 83 UK and US memory institutions was done by collecting and analysing data of a sample of heritage organisations' websites during the period of April-July 2020. The selection included major institutions from both countries (e.g. based on visitor numbers in Wikipedia) plus a selection of smaller civic, historic and/or city museums. To understand what the digital offerings consisted of, we recorded through a survey both a description of each offering and the type/format of its content. Being aware of digitisation efforts, especially by larger institutions, to produce 3D interactive content, we wanted to find out how such visual content was deployed during the COVID crisis to address the needs of existing and newly emerging audiences. For this, we recorded offerings such as 360° virtual tours and interactive panorama/VR/AR type experiences and 3D objects, while also looking at interactive games and activities. We hypothesised that this type of content would have allowed audiences to engage more actively and access artefacts, museum exhibitions and physical spaces using visual and interactive mechanisms.

Yet, the results of the survey demonstrated that only a small number of the highlighted museum offerings (30 amongst the 922 offerings) during the pandemic were related to 3D content, as shown in Figure 2, enabling audiences to virtually visit heritage spaces, interact with collections or engage in learning activities. As shown in Figure 3, the percentage of 3D within these types of offerings was also low, as it represented between 12% and 16% of the overall content. Some indicative examples of 360° virtual tours and interactive panorama/VR/AR experiences include: a tour of the Royal Pavilion in Brighton (UK) [Roy20b], a virtual visit of the York Castle Museum via Google Arts and Culture [Goo20] and interactive exploration of the Vizcaya Museum and Gardens in the USA [Viz20].

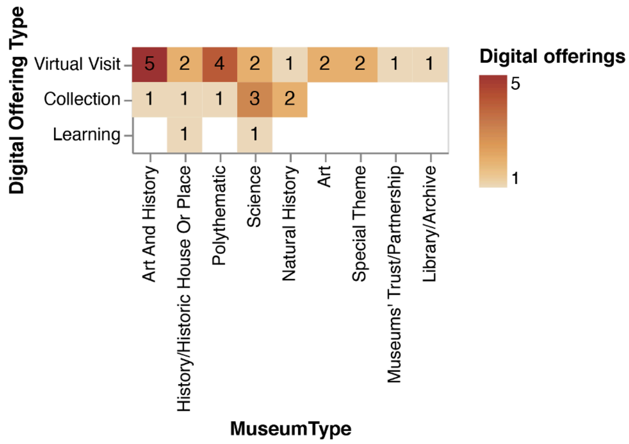

Figure 2: *3D content per offering type for all museum types.*

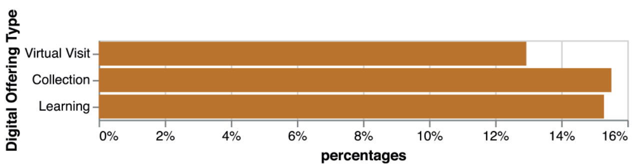

Figure 3: *Percentage of 3D content with respect to all offerings per offering type.*

As far as it concerns access to digital 3D models of museum artefacts, users' interaction with such offerings is facilitated through established and emerging 3D content platforms, such as Sketchfab, p3d.in, and Kompakkt [Ske20; P3d20; Kom20]; while libraries with printable models where museums host accounts also exist [Thi20; MyM20]. Sketchfab, as the most widespread platform of 3D content, hosts millions of 3D models with many amongst them coming from the heritage domain. In 2017, there were more than 500 museums' accounts on the platform [Mar] and this number is expected to be higher today. The British Museum, the Science Museum Group (UK), The Smithsonian Institution in the USA, and the Natural History Museum Vienna are amongst those disseminating 3D models of their collection objects through Sketchfab [The14; Nat20c; The17; The20]. These objects allow users to explore 3D models through interactions which are restricted mostly to view mode operations, i.e. zooming, rotating and panning with the use of a hand cursor. In some cases, users can interact with annotated points on the 3D geometry of the displayed artefact.

In the context of educational and leisure offerings, a wide range of online museum activities exists, targeting mostly educators and young users. Such online offerings range from teaching material [Ten20] and creative activities [Ash20; Art20] to interactive games for portable devices [Nat20a], webinars [Smi20], bedtime stories [Roy20a] and more. Amongst these offerings jigsaw puzzles are often developed to engage users in synthesizing a museum artefact in 2D [Yal20; App20; Roy20b].

In the realm of learning resources, the presence of 3D content is sparse. Some examples of activities include exploring 3D objects while proposing a set of questions to trigger thinking [Mus20a]; identification games using 3D models of animal skulls along with 2D content [Mus20b]; investigating annotated 3D models of natural history exhibits along with other audiovisual resources [Nat20b], and employing 3D digital and 3d printed models of paleontological data as vehicles for exploration within the curriculum [ZPP*20]. Such examples demonstrate an effort to incorporate 3D visual content in educational resources, supporting though limited interaction capabilities. Moreover, and while physical puzzles replicating artefacts, monuments or specimens have been produced through digital fabrication to be used in formal and informal learning settings [MWL*15; AMN13; 19], there have not been any efforts to make a similar activity available online. To the best of our knowledge, the proposed activity is innovative not only in terms of advanced interaction modes but also in terms of offering the experience of the puzzle pot assembly both in the digital and the physical world.

3. Development of the interactive puzzle game

The development of the online experience is inspired by our previous research on the development of a 3D printed physical puzzle [ESW20]. The artefact selected for this puzzle activity is an Iron Age pot, a funerary urn, which was found in 1910, probably used by the inhabitants of a small farming settlement overlooking the cliffs and sea in Saltdean (UK).

Early in the development process, it was agreed that the comparison between the physical and digital experience of assembling a puzzle was not straightforward due to the different contextual circumstances, namely differences in the setup and nature of the activity, as well as the recruitment of a different sample used for the evaluation of the activity. De Kegel and Haahr provide an extensive survey of procedural puzzle generation for puzzles both in a physical and digital format [DH20]. According to their classification the proposed activity falls within the assembly puzzle activity, as it requires a number of shapes to be assembled into a larger shape without overlap or gaps. Both 2D and 3D volumetric puzzles are reviewed. This review demonstrates that beyond interlocking physical puzzles [SFC12] there is a lack of research into 3D digital puzzles as well as the interfaces required for users to easily understand the game mechanics.

Hence, given the lack of digital interfaces for 3D puzzles, as opposed to more popular 2D puzzle activities targeted to young children, it was not possible to incorporate available interfaces and interactions to manipulate the pieces and the fitting process. As such, any comparison between the interactivity/usability of a digital 2D puzzle and a 3D puzzle can be quite difficult to achieve because of the variety of contextual parameters that might not be easy to control or capture online.

(a) *3D puzzle activity within archaeological gallery at the Brighton Museum and Art Gallery.*

(b) *3D digital puzzle activity using a similar interaction to the physical activity.*

Figure 4: *Physical and digital counterpart of 3D puzzle game.*

Nevertheless, we informed our approach to create the user interface and interactivity based on the experience gained during the creation of the physical experience. Figure 4a illustrates the physical 3D puzzle activity. This involves a central *core* area which displays line clues for the users to find the correct match and attach the puzzle pieces. Once the user identifies the match, they can attach the puzzle piece to the core via magnetic attachments embedded in the 3D printed pieces.

Similarly to the physical activity, the digital version (shown in Figure 4b) is also designed using a 3D *core* as a base rotating around a central pivot point to allow users to fit the pieces. In the physical experience, this rotation is restricted only to one axis of rotation as shown by the fixed handles in figure 4a. In the digital version, we removed this restriction so that the user could rotate the core around the three axes freely.

Designing the interaction for fitting the pieces in the 3D digital puzzle required careful consideration. Given the various degrees of freedom the user has in moving both puzzle core and potentially the puzzle pieces, we decided to limit the movement which can be applied to the puzzle pieces, to avoid users getting easily lost or frustrated by not finding the correct match. Instead, the puzzle pieces are loaded and presented to the user statically aligned with the viewing plane, where they remain, until the user finds their correct position. For this, the user can rotate the core piece along with the (partially assembled) pot underneath to find the right alignment for each newly selected piece.

To facilitate attaching the puzzle piece on the core, we used transparency when displaying the puzzle piece, while still being able to see the designs/colours on it, and also enabled the option for the user to increase/decrease this transparency. In this way, users can either use the coloured core or the colours/designs on the texture of the puzzle piece to facilitate assembly. In this way, we avoid hiding the core behind the puzzle pieces and potentially confusing the user due to occlusions. Extra clues can be also activated and these include showing a transparent duplicate of the chosen piece already attached on the core so that users can easily see where the piece that they have chosen should be attached.

Three.JS [Thr21] and Angular framework [Goo21] were used for the implementation of the digital puzzle as an interactive web application. The following subsections will describe the development of the 3D content and the deployed functionality to achieve the various elements and interactions described above.

3.1. Generating 3D model of puzzle pieces

To obtain a 3D model of the selected archaeological artefact we made use of 3D scanning to create the outer surfaces of the pot. To reconstruct the internal part of the urn which was not acquired by the scanner, we generated additional faces using a modifier in Blender to create the external wall with a 10 mm thickness.

Thereafter, we used the method described in [ESW20] to generate the individual puzzle pieces. The approach involves creating "puzzle pieces" (shards, or *fragments*) using Boolean operators on a fractured sphere. To obtain the fractured sphere, our method hierarchically subdivides the spherical domain until a target number of fragments is reached. Moreover, we also fractured the 3D model of the core geometry, which has been generated using Boolean operators, with the same algorithm to deploy these as clues by using different colours for each 3D fracture. In this way, the user visualises the equivalent to the puzzle boundary lines in the physical puzzle (see Figure 4a and Figure 4b for reference).

In total, we generated 16 pieces by using fractal curves of low amplitude as illustrated in Figure 5. The pieces were generated with a high resolution (approximately 350K vertices) 3D model of the pot, although later in the process the pieces were decimated. This initial high-resolution model was required to support extracting and transferring high-quality colour information, as detailed in

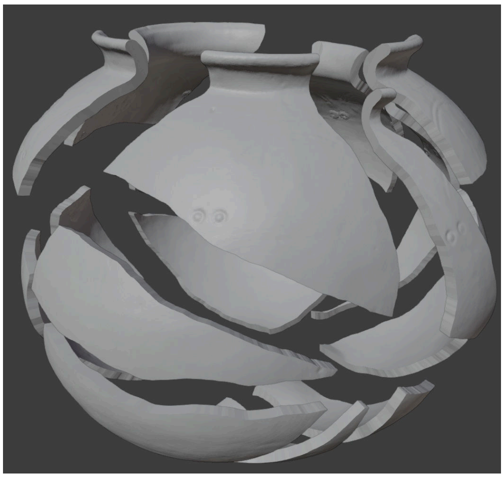

Figure 5: *Fractured puzzle pieces using a* hierarchical fracture *approach. [ESW20]*

(a) *Digital photographs providing colour information for the 3D models of the puzzle pieces.*

(b) *Colour projected onto the 3D model.*

Figure 6: *Colour information is projected from raster images onto the 3D model to produce textures.*

the following subsection, to the lower quality 3D model used for the interactive game application. The resulting number of pieces are comparable to the number in the physical puzzle; although the physical puzzle already presents the user with some of the pieces glued onto the base of the core in order to be used as clues.

3.2. Texturing the puzzle pieces

After producing the puzzle pieces, the next step was to generate high-quality textures to show the accurate colours and curvilinear designs of the original pot. In the physical process, an artist recreated the design. For the digital counterpart, we decided to deploy the digital photographs (see Figure 6a) which were acquired for texturing the puzzle pieces.

For this, we extracted colour information from the "raster" images or digital photographs. The process involved setting up correspondences between digital photographs and the 3D model using a raster alignment algorithm in MeshLab [RCD*13] so that the information could be mapped. To acquire colour information at a higher resolution, we projected the colour from the raster images onto the vertices of the high-resolution 3D model using MeshLab [CMR*99]. Thereafter, we transferred the colour vertex information from the 3D model, as shown in Figure 6b, to each puzzle piece extracted through the process described in section 3.1. We then saved all the 3D models as PLYs with colour per vertex for each puzzle piece.

To produce textures for the low-resolution puzzle pieces, we *baked* the colour per vertex information into a texture. For this, we generated a stretch-minimal UV parametrisation for each 3D model. Using this UV mapping, we baked the colours per-vertex information and further decimated the puzzle pieces. The resulting 3D models are shown in Figure 1. These were saved as in the GLTF standard, and the texture was stored as a separate JPEG file.

3.3. Interaction

The interactive application was implemented using an Angular component [Goo21] with a Three.JS puzzle viewer. The viewer provides the following functionalities: i) loading the 3D models (as the user selects the pieces); ii) displaying the 3D model of the core; iii) allowing the user to rotate this freely around the 3-axes; and iv) fitting the pieces to the core. The system keeps a timer that is activated when the user selects the first piece. Once all the pieces are found, the timer stops and the users' time is recorded along with other information (see Section 3.4 for more details).

Two 3D scenes are used in the implementation of the puzzle viewer: a primary 3D scene where the core is displayed and the puzzle is assembled, and a secondary 3D scene that contains the 3D puzzle piece which is being loaded and a camera. The 3D scenes are rendered into framebuffers in a two-pass rendering process, implemented as render targets in Three.JS, and rendered on a texture, one with additional transparency so that the background is visible.

Furthermore, to achieve this desired functionality of allowing the user to assemble the 3D puzzle, we implemented the following set of features:

Selecting a piece The user can select one piece amongst the 16 options by clicking on the buttons presented on the web interface. We used a thumbnail image on the button, shown in Figure 4b, to help users remember the pieces, and we placed first the pieces around the rim as these are the easiest to start with; something demonstrated by the physical experience of the puzzle assembly too, as users would mostly start by assembling the shards around the pot's rim.

Displaying a puzzle piece Once the user clicks on a button, the puzzle viewer loads the 3D model and presents a static view of the piece. For this, we computed the best orientation for the puzzle piece by finding the angle of rotation which would result in an orthogonal-top view of the piece. We found this angle θ by using the dot product and the vectors $v1$, which is the camera vector, and $v2$, which is the vector from the centre of the scene to the centre of the bounding box of the 3D model. We then loaded the puzzle piece into the secondary scene which is rendered into the second framebuffer with transparency for the user to be able to visualise the primary scene (see Figure 1).

Fitting a piece To interact with the puzzle viewer, the user performs a rotation of the partially assembled puzzle on its central pivot point. To find a correct match, the system performs a check based on the distance between the cameras' positions in the 3D scenes (p and q). We computed the distance using $d(p,q) = \sum_{i=1}^{n} |p_i - q_i|$ and allowing for a tolerance for the d value (in this case we use $d <= 3$).

Loading clues Users can increase or decrease the transparency of the puzzle pieces when these are loaded via a slider. The piece never becomes completely transparent. In this way, the user has more control to visualise the texture clues or see what is behind the puzzle piece. A further extra clue is provided using a slide toggle which allows the user to display the puzzle piece already fitted in its correct position with almost full transparency as shown in Figure 1.

3.4. Recording user's interaction

The interactive application features JSON connectivity to a Firestore JSON database in order to log user activity. Thus, it is possible to analyse the user behaviour in terms of timings for each piece assembly, and the use of the clues within the system. As such, we measured the following data: order in which the user loads pieces; whether clues where used per piece; the level of transparency used per piece; time for puzzle piece completion; time for whole puzzle completion; and rotation of the trackball interface (both azimuthal and polar angles). We also recorded information regarding the system used, including Operating System, browser, domain name used (as we included a link within the survey and users could also type directly the URL of the puzzle activity). This information was later retrieved using python library Pandas and visualisations of the data were produced using the Altair declarative visualization Python library [Alt21]. The resulting analysis is presented in the following section.

4. Preliminary evaluation

A pilot online survey was launched to understand how users engaged with the 3D interactive puzzle activity of the pot artefact and then "translate" their performance, rating and comments into requirements for other interactive use of 3D models. Through this initial survey, we also aimed to investigate the overall impact of such online offerings to better contextualise heritage collections and enhance learning and appreciation, particularly when access to the museum might not be possible.

The survey was released online in July 2021 and the data from 14 participants are presented here. Due to the small sample size, the analysis of users' data does not aim to provide generalisations but rather to shed light on interactions, and showcase the variety of responses and tendencies in their feedback. More data are expected to be collected in the following months to enrich the evaluation.

4.1. Evaluation design and participants

Both quantitative and qualitative data were gathered through the survey in order to record:

- Participants' information, background, past experiences in interacting with 3D content, as well as interests in 3D digital offerings and motivation to deploy such content; measured with nominal and ordinal quantitative data.
- User experience aspects with particular emphasis on usability, including efficiency, learnability and user satisfaction; measured with ordinal quantitative data.
- User experience aspects through a set of *Generic Learning Outcomes* to examine awareness, knowledge, interest, attitudes, skills and behavioural effects of the experience as suggested in established cultural heritage evaluation frameworks and visitor studies [Art14; DHU16]; measured with ordinal quantitative data and open-ended qualitative comments.
- Log data to provide further evidence about users' performance in the puzzle assembly; these include the use (or not) of available clues, order of pieces' selection, timings and amount of rotation for the assembly of each piece.

Adult participants (18 years old and older) from any ethnic background and gender were recruited through mailing lists of Information Technology (IT) and heritage subjects' students, as well higher education and museum, gallery, archive professionals.

4.2. Findings

Qualitative data were analysed by using the qualitative data analysis software NVivo by QSR international. The preliminary findings aim to illuminate various aspects of the online puzzle assembly activity to reflect on: how the users who are interested in online cultural heritage interactive resources respond to the activity; the impact of such applications at multiple perceptual levels of the participating audiences; how suitable 3D digital interactive puzzle activities are to better contextualise heritage artefacts; and lastly, the possible commonalities and differences between the actual access to the physical activity in the museum and the 3D interactive activity on the web.

In total, 14 participants took part in the activity and completed the online survey. Amongst them, 7 were men, 6 were women and 1 preferred not to say. As shown in Figure 7 most users (8 people) belonged to the age groups between 25 and 49 years old. The ages above 50 years old were represented with 4 users in total and there was only a younger user between the age of 18-24 years old. 13 users amongst the 14 participating had higher education qualifications. When looking at people's interests and motivation, 7 users stated that they were interested in exploring 3D cultural heritage content for education-related purposes; whereas 6 users were mostly looking at ways to enhance participation and involvement in the museums' events and activities. One user did not have any particular interest or motivation.

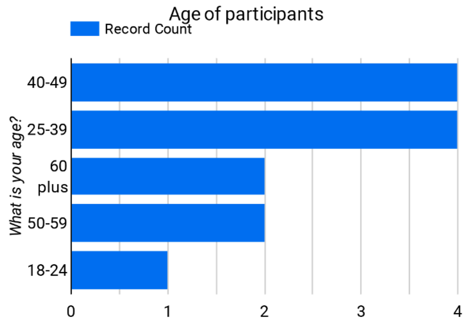

Figure 7: *Participating users' age.*

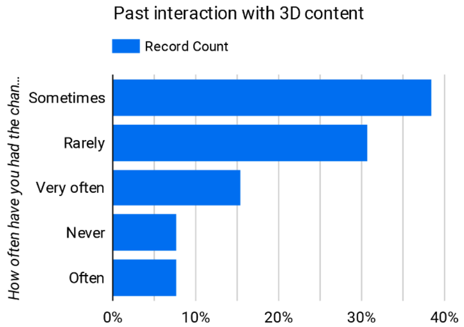

Figure 8: *Users' interaction with 3D content.*

As far as it concerns previous experience with 3D content, the majority of users as shown in Figure 8 had sometimes interacted with 3D resources (5 users) and 4 users had the chance to experience this kind of offerings very often or often. The most popular type of content people referred to with respect to past interactions were VR/AR applications and then 3D models of objects and 3D maps. Some users (2 people) had also experience with 3D printed artefacts. Another element that is worth mentioning about past interactions is that amongst the 5 users who rarely or never had the opportunity to interact with 3D content, 3 were working in the heritage domain. Yet, they had not been exposed to or offered many opportunities to experience 3D digital heritage resources.

As mentioned before, all users completed the puzzle assembly and log data about their performance were also recorded. By looking at the data, we seek to understand whether there was a correlation between the shape of a particular piece, the order in which the piece was selected, the amount of movement on the orbit controls (manipulated by the user mouse), and the time it took the user to find the right position for the piece. However, the data seem inconclusive as they did not show strong correlations. This gives us further confidence that the overall time it tasks a user to assemble the puzzle is not dependent on the characteristics of individual pieces, but on the overall assembly challenge. For example, Figure 9 shows the accumulated timings spent by the user fitting each consecutive piece, starting from when the user selects the piece (clicks on the button) and finishing when the piece is fitted. The average is shown in a red line.

Moreover, the longest time for the overall puzzle assembly activity was 9 minutes and 5 seconds and the shortest time was 2 minutes and 4 seconds. These timings take also into account the time

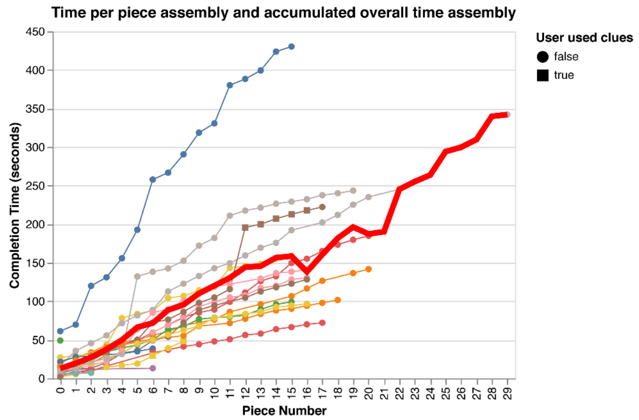

Figure 9: *Accumulated time spent by all users fitting each of the 15 puzzle pieces. We count the time from the moment the user selects the piece from the menu displaying all the pieces, and stop counting only when the piece is correctly fitted.*

the user spent deciding which piece to select. The mean time for the assembly of each puzzle piece is 17.32 seconds. The mean time for the overall puzzle assembly is 5 minutes and 35 seconds. This is considerably higher than the maximum time spent at the gallery to assemble the physical puzzle, which was around 3 minutes.

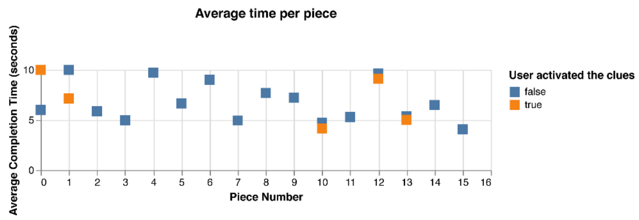

Figure 10: *Average time spent by users finding the correct position for each of the 15 puzzle pieces during the assembly process. Two different colours are used to show averages when users activated the clues and when they did not. For those pieces that only have one time recorded, users did not activate the clues at all.*

Figure 10 further presents the average time spent to place a piece on the puzzle core with or without the use of extra clues. The longest time spent for one piece fitting was 1.42 minutes and the shortest time 0.5 seconds. Figure 11 presents the average rotation per piece with and without the use of clues.

Additional findings about the overall usability/utility of the 3D digital puzzle pot assembly are presented in Figure 12. Overall activity satisfaction and utility to perceive the heritage artefact received higher ratings. As such, users agreed that the 3D digital puzzle was helpful to get the overall feeling and appearance of the pot compared to having access to the physical artefact in the museum. Some users also reported that they had difficulties with the type of interactions deployed in the puzzle activity, while others were not fully convinced about the helpful contribution of clues to facilitate assembly. As such, puzzle learnability received the lowest average rating, while users' comments later corroborated some dif-

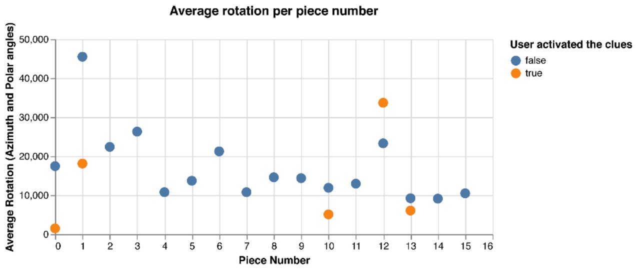

Figure 11: *Average degrees of rotation resulting from users manipulating the core piece before finding the correct position for each one of the 15 puzzle pieces during the assembly process. Two different colours are used to show averages when users activated the clues and when they did not. For those pieces that only have one time recorded, users did not activate the clues at all.*

1	2	3	4	5	avg
Overall efficiency: How did you get along with the activity of the 3D puzzle?					
1	1	7	4	1	**3.21**
Puzzle learnability: How easy was to assemble the 3D digital puzzle and navigate around the activity?					
1	4	5	4	0	**2.85**
Clues utility to facilitate assembly: How helpful have clues, such as the colours on the surface of the pot and the shard lines, been to help you assemble the puzzle?					
1	5	2	3	3	**3.14**
Activity satisfaction: How satisfied are you with the 3D digital puzzle activity of the artefact?					
1	3	1	6	3	**3.5**
Puzzle utility to perceive physical exhibit: How useful is the 3D digital puzzle to get the overall feeling and appearance of the pot compared to having access to the physical artefact in the museum, if this was possible?					
0	2	5	5	2	**3.5**

Figure 12: *Results of the usability/utility rating on a 5-point Likert scale with 1 being the lowest and 5 being the highest rate.*

1	2	3	4	5	avg
Knowledge/awareness: The exploration of the 3D digital puzzle of the artefact helped me to discover more about the original pot/ the museum/the way archaeologists work.					
2	4	4	3	1	**2.78**
Engagement/interest: I enjoyed the experience of the 3D digital puzzle of the artefact.					
1	1	3	6	3	**3.64**
Value: There is value in having 3D digital activities related to artefacts available to audiences online.					
0	1	1	4	8	**4.35**
Attitudes: Similar experiences with the provision of 3D digital activities related to artefacts online would change the way I think about visiting a museum.					
2	1	4	4	3	**3.35**
Skills: I have used different skills for the assembly of the 3D digital puzzle of the artefact.					
0	3	4	0	7	**3.78**

Figure 13: *Rating the impact of the activity at multiple perceptual levels on a 5-point Likert scale with 1 being the lowest and 5 being the highest rate.*

ficulties in finding out and learning how the puzzle works. Some users highlighted the lack of further instructions on how controls work to fulfil the task; others did not realise how to change their selection of piece; and some mentioned that the existence of similar neighbouring colours on the puzzle core did not always allow to clearly distinguish the shape of the required piece. On the other hand, positive comments on the overall impression and efficiency of the puzzle pot experience referred to an activity that was “good fun” and “a good idea”, which could also be useful to “reconstruct images like some of the Egyptian statues and faces that have been defaced”.

Apart from the aspects of user experience (UX) presented previously, the survey sought to understand the impact of such interactive 3D digital activity in terms of *Generic Learning Outcomes*, i.e. enhancing users’ knowledge/awareness; strengthening their engagement/interest; adding value to the cultural heritage experience; possibly changing their attitudes towards visiting a museum; deploying a variety of skills for the puzzle assembly. The investigation of these topics belongs both to the realm of UX and perceptual or learning outcomes in visitor research [DHU16; Art14]. When completing the survey, all users were asked how much they agree with statements (presented in Figure 13) about the contribution of the 3D digital puzzle pot assembly to the impact aspects mentioned above.

As shown in Figure 13, amongst the 14 participants most (10 people) had a neutral or negative impression about the contribution of the application to enhance their knowledge and awareness about the object or the way it would have been assembled by archaeologists. In their comments, many users highlighted the lack of context to enrich the experience and discussed about a “construction exercise”. Many suggested presenting the activity as part of a story about an archaeological excavation or “winning” some extra information once the puzzle is complete.

Interest and engagement, on the other hand, received higher ratings with 9 users feeling positive about the activity contributing to this aspect of their experience. Participants mentioned that this was a “fun game”; that they prefer “manipulating” objects; that the 3D character of the activity is better than a 2D jigsaw puzzle; and that there are many possibilities for this kind of offerings. Yet, some people noted that the activity would be better positioned within an experience that better contextualises the pot or that they would prefer more creative ways for object gamification.

When examining the value of 3D interactive offerings, the vast majority of users (12 users) agreed that such activities and content positively contribute to cultural heritage experiences. Some participants referred to 3D objects that would be a “nice addition to any digital museum experience"; that it would allow for better exploration of the museum artefacts; and that it could enhance accessibility for those who might not be able to visit the museum, while also reaching wider audiences. Some scepticism also exists, as some users mentioned that the type of the chosen artefact would determine the value of the offering, while another user said that even though there might be some value, "3D for the sake of 3D is not good enough".

With regards to the attitudinal aspect of the experience, most users agreed that such activities might change the way they think about visiting a museum (7 users). Participants pointed out that such activities "break" the passive viewing experience of artefacts; might motivate people to pay more attention to particular exhibits and complement the visit, and "encourage a vibrant visitor experience". However, some users would go to the museum anyway and mentioned that the physical visit constitutes a stronger experience that the digital experience cannot substitute. One user, though, thought that 3D interactive activities might even become more fascinating than an actual visit to the museum.

The skills deployment aspect of the experience acquired mostly edge positive ratings, as 7 people strongly agreed that they used different skills for the puzzle assembly. Participants mentioned spatial, thinking and information technology skills. This response confirms what other studies have highlighted in terms of the potential of 3D interactive technologies to help with spatial thinking and manipulation. Nevertheless, some users expressed their desire to deploy more skills through more extended manipulations or interactions with the 3D digital puzzle.

Lastly, participants' general comments revealed that they would want to see more of these online offerings targeting both children and adults, yet similar activities should be contextualised to enhance learning and appreciation of heritage artefacts. Clearer and even richer interactions are also desirable, to avoid using technology for the sake of technology itself.

5. Discussion and Conclusions

Our research contributes to enhancing the community's understanding of the type of interactive experiences that could be created with the 3D content which is increasingly available within heritage institutions. As such, the paper contributes a set of user interactions for manipulating 3D puzzles, and a 3D puzzle game which is novel as not many 3D puzzles of cultural heritage artefacts are available over the web. The paper also offers some insights into the user interaction in terms of usability and performance when examining the physical and digital experiences.

The results of the pilot user survey reflect on how 3D content can support the interpretation of cultural heritage. Although the sample is small to provide generalisations, there is some evidence of the advantages that this type of interactive experience has for users, including promoting spatial skills, enriching the museum experience and allowing for deeper engagement with the content. However, the research also highlights that the connection with the actual heritage artefact should remain throughout this engagement so that the experience does not get derailed by a technology-led approach.

Another common element is that both the physical and digital activity seem to satisfy the majority of users and they would both motivate people to visit a museum and develop less passive engagements with artefacts. Nonetheless, digital users will have to become familiar with such interactions with 3D content, whereas the type of interactions will have to become explicitly clear to users before they try such activity in the first instance.

While the web-based technologies used for the research enable a wide-user reach, they also bring specific challenges in terms of being cross-platform and cross-hardware. As such, technical challenges remain for streaming content for lower-capability devices while being responsive and providing high-quality graphics.

The analysis of this sample of user responses further indicates that 3D is still a largely under-explored type of content, with people not being exposed to 3D digital content even though they might come from a heritage-related background or affiliation. Nevertheless, as most users reported interest to explore 3D digital activities for educational purposes as well as having an interest in engaging with museums, there is still great prospect for developing systems that allow different types of interactions with 3D content. This could allow for creative and educational engagement.

We believe that the deployment of 3D interactive activities has great potential for strengthening people's interest and most importantly for enhancing accessibility and reaching wider audiences. The physical activity supports engagement through interactivity too but reaches only the audiences visiting the museum.

Future research will explore expanding the evaluation survey. It will also investigate interoperable frameworks to facilitate the provision and access to 3D content that both contextualise the heritage experience and allow for deeper interactivity with the content. This will enable institutions to offer a holistic experience of CH resources to audiences, without necessarily depending on having physical access to collections - a need that is expected to be prevalent within the next few years.

References

[19] "Abstracts". *Journal of Morphology* 280.S1 (2019), S1–S244. DOI: https://doi.org/10.1002/jmor.21003 3.

[Alt21] ALTAIR DEVELOPERS. *Altair: Declarative Visualization in Python*. https://altair-viz.github.io/. [Accessed 26-July-2021]. 2021 6.

[AMN13] AMNH. *Students Use 3D Printing to Reconstruct Dinosaurs*. [Accessed 26-July-2021]. 2013. URL: http://www.amnh.org/explore/news-blogs/education-posts/students-use-3d-printing-to-reconstruct-dinosaurs 3.

[App20] APPLETON MUSEUM OF ART. *Online Jigsaw Puzzles*. [Accessed 26-July-2021]. 2020. URL: https://www.appletonmuseum.org/online-resources/online-jigsaw-puzzles/ 3.

[Art14] ARTS COUNCIL ENGLAND. *Inspiring Learning for All*. [Accessed 26-July-2021]. 2014. URL: http://www.artscouncil.org.uk/advice-and-guidance/inspiring-learning-all-home-page 6, 8.

[Art20] ART INSTITUTE CHICAGO. *Get Creative at Home*. [Accessed 26-July-2021]. 2020. URL: https://www.artic.edu/visit-us-virtually/create-and-learn/get-creative-at-home 3.

[Ash20] ASHMOLEAN MUSEUM OXFORD. *Digital Sketchbooks*. [Accessed 26-July-2021]. 2020. URL: https://www.ashmolean.org/learning-resource-digital-sketchbooks 3.

[CH15] CSIKSZENTMIHALYI, M. and HEMANSON, K. "Intrinsic Motivation in Museums : Why Does One Want to Learn ?": *Public Institutions for Personal Learning, Establishing a Research Agenda*. Ed. by DIERKING, L., FALK, J., and AMERICAN ASSOCIATION OF MUSEUMS. 2015. ISBN: 0931201241 2.

[CMR*99] CIGNONI, PAOLO, MONTANI, CLAUDIO, ROCCHINI, CLAUDIO, et al. "Preserving attribute values on simplified meshes by resampling detail textures". *The Visual Computer* 15.10 (1999), 519–539 5.

[DH20] DE KEGEL, BARBARA and HAAHR, MADS. "Procedural Puzzle Generation: A Survey". *IEEE Transactions on Games* 12.1 (2020), 21–40. DOI: 10.1109/TG.2019.2917792 3.

[DHU16] DIAMOND, JUDY, HORN, MICHAEL, and UTTAL, DAVID H. *Practical evaluation guide: Tools for museums and other informal educational settings*. 3rd. Rowman & Littlefield Publishers, 2016. ISBN: 1442263539 6, 8.

[ESW20] ECHAVARRIA, KARINA R., SAMAROUDI, MYRSINI, and WEYRICH, TIM. "Fracturing artefacts into 3D printable puzzles to enhance audience engagement with heritage collections". *ACM Journal of Computing and Cultural Heritage (JOCCH)* 13.1 (Jan. 2020), 23 pages. DOI: https://doi.org/10.1145/3351343 2–5.

[FD13] FALK, JOHN H. and DIERKING, LYNN D. *The Museum Experience Revisited*. 1st. Walnit Creek, California: Left Coast Press Inc., 2013. ISBN: 9781611320442 2.

[Goo20] GOOGLE ARTS & CULTURE. *York Castle Museum*. [Accessed 26-July-2021]. 2020. URL: https://artsandculture.google.com/streetview/york-castle-museum/uQGjuESC2b_VTw 3.

[Goo21] GOOGLE. *Angular Framework*. https://angular.io/. [Accessed 26-July-2021]. 2021 4, 5.

[Kom20] KOMPAKKT. *Kompakkt platform*. [Accessed 26-July-2021]. 2020. URL: https://kompakkt.de/home 3.

[Mar] MARCHOU, RAPHAEL. *Over 500 Cultural Institutions have joined Sketchfab*. [Accessed 26-July-2021]. URL: https://blog.sketchfab.com/500-cultural-institutions-joined-sketchfab/ 3.

[Mus20a] MUSEUM OF LONDON. *Explore 3D prehistoric objects*. [Accessed 26-July-2021]. 2020. URL: https://www.museumoflondon.org.uk/schools/learning-resources/3d-objects-stone-age-to-iron-age 3.

[Mus20b] MUSEUM OF SCIENCE. *Mystery Skulls*. [Accessed 26-July-2021]. 2020. URL: https://virtualexhibits.mos.org/mystery-skulls/ 3.

[MWL*15] MILES, HELEN C., WILSON, ANDREW T., LABROSSE, FRÉDÉRIC, et al. "Alternative Representations of 3D-Reconstructed Heritage Data". *J. Comput. Cult. Herit.* 9.1 (Nov. 2015). ISSN: 1556-4673. DOI: 10.1145/2795233 3.

[MyM20] MYMINIFACTORY. *MyMiniFactory platform*. [Accessed 26-July-2021]. 2020. URL: https://www.myminifactory.com 3.

[Nat20a] NATIONAL GALLERY OF ART. *"NGAkids Art Zone" for iPad*. [Accessed 26-July-2021]. 2020. URL: https://www.nga.gov/learn/kids-app.html 3.

[Nat20b] NATURAL HISTORY MUSEUM. *Come face-to-face with Dippy the dinosaur - explore his skull in 3D*. [Accessed 26-July-2021]. 2020. URL: https://www.nhm.ac.uk/discover/dippy-the-dinosaur-3d-skull.html 3.

[Nat20c] NATURAL HISTORY MUSEUM VIENNA. *Natural History Museum Vienna on Sketchfab*. [Accessed 26-July-2021]. 2020. URL: https://sketchfab.com/NHMWien 3.

[P3d20] P3D.IN. *p3d.in platform*. [Accessed 26-July-2021]. 2020. URL: https://p3d.in 3.

[PS16] PALIOKAS, I. and SYLAIOU, S. "The Use of Serious Games in Museum Visits and Exhibitions: A Systematic Mapping Study". *2016 8th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES)*. Sept. 2016, 1–8. DOI: 10.1109/VS-GAMES.2016.7590371 2.

[RCD*13] RANZUGLIA, GUIDO, CALLIERI, MARCO, DELLEPIANE, MATTEO, et al. "MeshLab as a complete tool for the integration of photos and color with high resolution 3D geometry data". *CAA 2012 Conference Proceedings*. Pallas Publications - Amsterdam University Press (AUP), 2013, 406–416. URL: http://vcg.isti.cnr.it/Publications/2013/RCDCS13 5.

[Ree09] REEVE, JOHN. "Prioritizing Audience Groups". *The Responsive museum: Working with Audiences in the Twenty-First Century*. Ed. by LANG, CAROLINE, REEVE, JOHN, and VICKY, WOOLLARD. 2nd. Farnham, Surrey: Ashgate, 2009. ISBN: 9780815346616 2.

[Roy20a] ROYAL MUSEUMS GREENWICH. *Enjoy a bedtime story with Ted*. [Accessed 26-July-2021]. 2020. URL: https://www.rmg.co.uk/schools-communities/eyfsks1-learning-home 3.

[Roy20b] ROYAL PAVILION & MUSEUMS TRUST. *Virtual Royal Pavilion*. [Accessed 26-July-2021]. 2020. URL: https://360rpmt.org.uk 3.

[SEP20] SAMAROUDI, MYRSINI, ECHAVARRIA, KARINA R., and PERRY, LARA. "Heritage in lockdown: digital provision of memory institutions in the UK and US of America during the COVID-19 pandemic". *Museum Management and Curatorship* 35.4 (2020), 337–361. DOI: 10.1080/09647775.2020.1810483 2.

[SFC12] SONG, PENG, FU, CHI-WING, and COHEN-OR, DANIEL. "Recursive Interlocking Puzzles". *ACM Transactions on Graphics (SIGGRAPH Asia 2012)* 31.6 (Dec. 2012), 128:1–128:10 3.

[Ske20] SKETCHFAB. *Sketchfab platform*. [Accessed 26-July-2021]. 2020. URL: https://sketchfab.com 3.

[Smi20] SMITHSONIAN NATIONAL MUSEUM OF NATURAL HISTORY. "Education". (2020). [Accessed 26-July-2021]. URL: https://naturalhistory.si.edu/education 3.

[Ten20] TENEMENT MUSEUM. *Lesson Plans*. 2020. URL: https://www.tenement.org/lesson_plans/ 3.

[The14] THE BRITISH MUSEUM. *The British Museum on Sketchfab*. [Accessed 26-July-2021]. 2014. URL: https://sketchfab.com/britishmuseum 3.

[The17] THE SCIENCE MUSEUM GROUP. *The Science Museum Group on Sketchfab*. [Accessed 26-July-2021]. 2017. URL: https://sketchfab.com/sciencemuseum 3.

[The18] THEAUDIENCEAGENCY. *Museums Augience Report*. 2018 2.

[The20] THE SMITHSONIAN INSTITUTION. *The Smithsonian Institution on Sketchfab*. [Accessed 26-July-2021]. 2020. URL: https://sketchfab.com/Smithsonian 3.

[Thi20] THINGIVERSE. *Thingiverse - Digital Designs for Physical Objects*. [Accessed 26-July-2021]. 2020. URL: https://www.thingiverse.com/ 3.

[Thr21] THREEJS AUTHORS. *ThreeJS*. https://github.com/mrdoob/three.js. [Online; accessed 26-July-2021]. 2021 4.

[Viz20] VIZCAYA MUSEUM & GARDENS. *Virtual Vizcaya*. [Accessed 26-July-2021]. 2020. URL: https://tour.virtualvizcaya.org 3.

[Yal20] YALE UNIVERSITY ART GALLERY. *Online Jigsaw Puzzles*. [Accessed 26-July-2021]. 2020. URL: https://artgallery.yale.edu/jigsaw_puzzles 3.

[ZPP*20] ZIEGLER, MICHAEL J, PEREZ, VICTOR J, PIRLO, JEANETTE, et al. "Applications of 3D Paleontological Data at the Florida Museum of Natural History". *Frontiers in Earth Science* 8 (2020), 570. ISSN: 2296-6463. URL: https://www.frontiersin.org/article/10.3389/feart.2020.600696 3.