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3D Printing and Immersive Visualization for Improved Perception of Ancient Artifacts

Abstract

This article investigates the use of 3D immersive virtual environments and 3D prints for interaction with past material culture over traditional observation without manipulation. Our work is motivated by studies in heritage, museum, and cognitive sciences indicating the importance of object manipulation for understanding present and ancient artifacts. While virtual immersive environments and 3D prints have started to be incorporated in heritage research and museum displays as a way to provide improved manipulation experiences, little is known about how these new technologies affect the perception of our past. This article provides first results obtained with three experiments designed to investigate the benefits and tradeoffs in using these technologies. Our results indicate that traditional museum displays limit the experience with past material culture, and reveal how our sample of participants favor tactile and immersive 3D virtual experiences with artifacts over visual non-manipulative experiences with authentic objects.

1 Introduction

Object manipulation is an important element in understanding and interpreting past material culture. Tactile perception of physical qualities is important for feeling, interpreting, and understanding ancient artifacts. However, sight is often given priority over the other senses when people experience such kind of objects. Visitors of archaeological sites and museums are usually not allowed to touch archaeological remains for obvious reasons of conservation and preservation. Curatorial restrictions are intrinsic to ancient artifacts; however, they deprive visitors of "the possibilities to grasp the objects' material and sensorially perceptible characteristics, which are pre-existing and inherent, real and physical" (Dudley, 2010, 4).

In order to overcome the limitations related to the inability of handling objects in museums and archaeological areas, 3D technologies have been employed to provide new ways to experience with our material past. Significant recent efforts in this area have been made to well reproduce sensorial experiences with past material culture. Immersive virtual reality systems are one of the ways in which people can experience our material past by interacting with virtual reproductions of artifacts. Even if tactile feedback is not present, virtual manipulation experiences are rich and the approach has been increasingly used in muse-

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ums and research labs. In addition, museums and research facilities have recognized the value of 3D printing for research and for the presentation of artifacts to the general public. These new ways of presentation enhance multiple sensorial experiences with our past, and present new research questions on how people negotiate with the inauthentic.

In order to correctly explore the benefit of these new technologies, it is important to understand how experiences with 3D digital copies in a virtual environment and with real 3D prints differ from the usual visual experience people have with original artifacts preserved and displayed inside museums. We present in this article three experiments designed to investigate these points. We are particularly interested in how people interact with 3D digital copies of artifacts, 3D prints and digital reconstructions in an immersive stereoscopic system, and how these experiences differ from the visual experience with original artifacts and with tactile experiences with 3D prints. Even though many studies in computer and cognitive sciences have explored how people perceive specific characteristics of objects (e.g., weight, size, and density) through visual, tactile, and virtual experiences, little is known about how people perceive past material culture through the senses, and how experiencing ancient artifacts through different media affects the perception of our past. Through a set of experiments designed to investigate how people respond to 3D virtual and printed replicas of artifacts, this article addresses perception of artifacts with the goal of identifying improved experiences for displays in museums.

The remainder of the article is organized as follows. Section 2 discusses related work. Section 3 presents the first experiment, which investigates how people perceive physical characteristics of ancient artifacts and how different media affect this perception. Section 4 describes the second experiment, which investigates how people describe artifacts through bodily movements and how different media affect the production of gestures. This experiment evaluates the concept of considering both gestures and words part of a thinking process (McNeill, 1992, 2007). The analysis of gestures therefore helps to understand how people think and engage with artifacts and the virtual and 3D printed counterparts.

Section 5 presents the third experiment, which investigates how people engage with artifacts in different media states. This experiment was designed to collect metacognitive information on how participants considered each experience to be useful for the perception and understanding of the artifacts, and how engaging the experience was perceived to be in each condition. Finally, Section 6 discusses major findings and Section 7 concludes the article and proposes future research.

2 Background and Related Work

2.1 Studies on How We Think with Artifacts

Scholars in psychology and cognitive sciences argue that when people engage with material objects they think with them (Hutchins, 2005; Clark, 2003; Ratey, 2002; Wilson & Myers, 2000; Lakoff & Johnson, 1999; Varela, Thompson, & Rosch, 1991; Lave, 1988; Norman, 1988; Suchman, 1987; Cole, 1985). To explore how people use objects as vehicles of thought, David Kirsh (2009, 2010a, 2010b) used the example of a six-piece puzzle. In a physical condition, people can move these six pieces and physically try to assemble them and create an image. In a mental imagery condition (i.e., when people cannot touch the pieces), people virtually move these pieces in their head (i.e., mental rotation and assembly). Both activities (i.e., the physical and the mental) show how our thoughts include material objects (Kirsh, 2010a). When we think through external representations, we can compare objects, build on them, rearrange them (as shown by the example of the puzzle), recast them, and perform other types of manipulations. Through these activities we are able to deepen our understanding of objects. According to Kirsh (2010a) however, all these arguments focus on material vehicles that represent propositional thought (i.e., abstract logic) but artifacts may mediate thought differently. They may have more to do with non-linguistic thinking. The question here is: “How do people co-opt non-propositional objects for thought?” (Kirsh, 2010a, emphasis original). In other words, how do people engage with material objects?

Tactile perception of a real-life object is usually an active experience involving information gathered from a variety of senses related to touch, such as texture and temperature, as well as movement and position of the hands and fingers during identification (Gibson, 1979, 123–129). Touch provides an understanding of shape, size, and weight, and it is through this sense that people develop an understanding of other properties such as density and all key properties for the exploration of artifacts (Doonan & Boyd, 2008; Kirsh, 2010b). For example, assessing the weight of an object can be critical for determining its function. Through several experiments Klatzky and colleagues have shown that people are relatively competent at recognizing objects haptically (i.e., through the sense of touch). In one experiment Klatzky, Lederman, and Metzger (1985) asked blindfolded people to recognize common objects just by touching them, and these people did so with very few inaccuracies. Subsequent studies clarified how people haptically explore objects to recognize them. These studies show how people actively explore their environment, executing a series of specific classes of hand movements in search of the "perceptual attributes" (i.e., texture, size, weight, etc.) of objects (Lederman & Klatzky, 1990, 422).

However, similar studies have shown that the perception of certain characteristics is not merely a haptic phenomenon. For instance, some experiments have shown that when two equally heavy objects of different sizes are lifted, the smaller object is perceived as being heavier (*size-weight illusion*; Heineken & Schulte, 2007). This finding demonstrates a *visual bias* affecting the perception of artifacts. Heineken and Schulte (2007) have also shown that an object's weight estimation can be affected by the medium selected to present it (e.g., 3D digital reproduction vs. tactile experience with original objects), and that the more presence is experienced in a computer-generated environment, the more realistic digital objects appear. A complete digression on tactile and haptic illusion can be found in the survey proposed by Lederman and Jones (2011).

Tactile experience is also considered an effective means to interpret ancient artifacts. MacGregor (1999) suggests that haptic analysis of material culture is an avenue available to the archaeological interpretation of past sensory orders, and that this analysis is conceptually and functionally different from analyses made using static visual images. For instance, when scholars studied carved stone balls circulating in the Aberdeenshire region of Scotland during the third and second millennia BCE (1852–1855 BCE) they frequently made reference to their appearance (decoration and number of knobs) in support of the interpretation that these balls were used in a ceremonial context to enhance the social status of those holding them. Clearly, scholars privileged vision above all other senses. According to MacGregor, however, when someone holds a carved stone ball decorated with knobs and rotates it quickly, the object visually takes another form, becoming a complete sphere (i.e., the knobs visually disappear). This transformation of the objects could have been witnessed by a much larger group of people and may have been considered magical. In this case, the haptic analysis of the balls results in a new interpretation of the object function.

2.2 The Use of Technologies for Improving the Museum Experience: Haptic Interfaces, Augmented Reality, Virtual Reality, and Rapid Prototyping Techniques

The studies discussed here show how important it is to manipulate objects in order to activate thinking processes that help with the interpretation of past material culture. To respond to this need of "physical" manipulation, computer scientists have sought to develop complex systems that simulate the tactile experience with real-life objects. Over more than twenty years, they have designed devices able to reproduce the feel of physical contact with objects and the perception of tactile stimuli (i.e., *haptic interfaces* and *force-feedback*). Haptic interfaces (from now on HI) and force-feedback devices have been widely studied in the last 20 years (e.g., Jansson, 1998; Buttolo, Stuatt, & Chen, 2000; Gregory, Ehmann, & Ling, 2000; Jansson, Bergamasco, & Frisoli, 2003), and have been commercialized by companies such as SensAble and Immersion. Haptic systems have been designed for experimenting with texture feeling (Colwell, Petrie, Kornbrot, Hardwick, & Furner, 1998; Minsky, Ming, Steele, Brooks, & Behensky, 1990) or with weight feeling integrated in immersive virtual environments (Hummel, Dodiya, Wolff, Gerndt, & Torsten, 2013). A few studies show how HI can be applied to create virtual art and archaeology exhibitions wherein users interact with both the visual and haptic senses (e.g., CyberGrasp, 2013; Loscos, Tecchia, Frisoli, Carrozzino, Ritter Windenfled, Swapp, & Bergamasco, 2004; Brewster, 2001; Bergamasco, 1999; McLaughlin, Goldberg, Ellison, & Jason, 1999; Massie & Salisbury, 1994).

Although many projects in computer science have been concerned with reproducing real-life tactile experiences with material culture, these projects do not yet allow a widespread use of HI for 3D museum and research applications in heritage and archaeology.

Nonetheless, museums are keen on presenting their collections through the use of new technologies, to attract diverse audiences (e.g., Touching the Prado, 2015; Hetherington, 2000). Another key element to fill the gap between real and digital is augmented reality.

Augmented reality (AR) is a real-time view of real-world environments augmented by computer-generated sensory input such as sound, video, and graphics. Augmented reality, unlike virtual reality (VR), tries to enrich reality instead of just reproducing it (Kayalar, Kavlak, & Balcisoy, 2008; Magnenat-Thalmann & Papagiannakis, 2006; Benko, Ishak, & Feiner, 2004). As a result, the technology enhances one's current perception of reality. The effects of immersive virtual reality on scientific visualization, data analysis, and in human interaction tasks have been studied extensively (for an example of these effects in the domain of archaeology see Di Giuseppantonio Di Franco, Galeazzi, and Camporesi, 2012). Depth perception in VR has been demonstrated to reduce errors and time, to improve user performance in spatial tasks (Ragan, Kopper, Schuchardt, & Bowman, 2013; Ware & Mitchell, 2005), as well as to improve object manipulation (Lin, Sun, Chen, & Cheng, 2009; Ware & Balakrishnan, 1994). However, systematic underestimation of distances was found both with respect to real workspace measurements and to egocentric distances (Willemsen, Colton, Creem-Regehr, & Thompson, 2009; Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, & Beall, 2004; Witmer & Kline, 1998).

Tactile augmentation is considered an effective alternative mixed-reality technique for introducing tactile cues (Follmer, Leithinger, Olwal, Hogge, & Ishii, 2013, 417–426; Pureform, 2013; inFORM, 2013; Jansson et al., 2003; Jeonghun et al., 2003; Hoffman, 1998). This technique is very effective with dedicated hardware appliances in dedicated exhibit spaces such as CAVE environments, dark rooms, and virtual theaters (Kenderdine, Forte, & Camporesi, 2012; Camporesi & Kallmann, 2013; Forte, 2008; Carrozzino & Bergamasco, 2010). Economic resources and multidisciplinary collaborations are, however, not always available in order to create and maintain such complex dedicated hardware. To respond to the increased interest from museum experts in these technologies (vom Lehn & Heath, 2005; Grinter, Aoki, Szymansky, Thorton, Woodruff, & Hurst, 2002) about a decade ago some scholars were already concerned with the design of systems that allow museum specialists to build and manage virtual and augmented-reality exhibitions in an efficient and timely manner, just by using a database of 3D models of artifacts (Wojciechowski, Walczak, White, & Cellary, 2004). Research today has produced advanced, non-invasive, easy-to-use, and affordable technology, which allows users to easily create 3D models of real environments in just a few minutes (e.g., holding and moving a Kinect camera: Izadi et al., 2011; or transforming a picture into a 3D model thanks to 3D data-managing software: ReCap, 2015; Photoscan, 2015). People can interact with augmented 3D models through Multitouch Devices (Ch'ng, 2013) or affordable immersive devices, such as Oculus Rift (Oculus, 2015) and augmented visualization has started to play an increasingly large role within the strategic framework of the arts and humanities (Ch'ng, Gaffney, & Chapman, 2013).

Tactile perception of ancient artifacts can now be achieved thanks to recent technological advances that make it possible to physically reproduce ancient artifacts using 3D printers. Three-dimensional digital copies of artifacts can be printed using Rapid Prototyping (RP) techniques. RP is the process of creating physical objects from computer-generated programs (e.g., CAD and 3D Studio Max) using 3D prototyping machines that can build a 3D object out of liquid, solid, or powder material

(Bradshaw, Bowyer, & Haufe, 2010, 6–12; Chua, Leong, & Lim, 2010). RP is applied to many fields, such as architecture, education, and healthcare (Bradshaw, Bowyer, & Haufe, 2010, 12; Chua, Leong, & Lim, 2010). Recently, this technique has been used in projects addressing preservation and reproduction of cultural heritage. For instance, a few companies are now experimenting with art museums to 3D print famous paintings with high-quality colors, to capture the "physical presence of these paintings" (Relievo, 2013; Alberge, 2013). With the notion of "physical presence," some scholars suggest that texture/relief is as important as colors to understand the uniqueness of a painting. Van Gogh, for instance, used thick layers of colors (i.e., a thick impasto) to create games of lights and shadows in his paintings.

While several works have explored the use of virtual reality replicas or 3D prints in different ways, no study has been performed to date with the specific goal of understanding the advantages and tradeoffs in using these modalities for the perception of artifacts.

Given the significant recent increase in the number of projects reported in the literature that incorporate 3D digital replicas and/or 3D prints of artifacts (e.g., Carrozzino & Bergamasco, 2010; Bruno, Bruno, De Sensi, Luchi, Mancuso, & Muzzupappa, 2010; White, Petridis, Liarokapis, & Plencinckx, 2007), investigating the value of these new technologies for the perception of our past becomes extremely relevant and important.

The main contribution of this paper is therefore to provide a first study focused on understanding the benefits given by these new technologies. We are not aware of previous work investigating the same questions as the ones addressed in this paper. The next sections present our experiments and results.

3 Experiment 1

In this first experiment, we have investigated how people perceive archaeological objects under different interaction modes: (1) visual examination, (2) three-dimensional immersive visualization, and (3) three-dimensional printed replica interaction. This experiment was designed to uncover which medium best enables the perception of the innate qualities of an artifact.

Figure 1. *Participant in the Look condition.*

3.1 Description of the Experiment

We have collected information about how people describe and interact with objects reproduced using different media:

1. *Look* (i.e., real-life visual examination) condition: participants viewed objects in a display case of 25 × 25 cm located on a table (see Figure 1). A caption with information on provenance, age, and size of each object was placed outside the display, 3 cm behind it. The participants in this condition were asked to stand in front of the display window, look at the object, read the caption, and then, looking at the camera, describe the object and eventually guess the function of the object in the past. The camera was located on the opposite site of the table (i.e., opposite in relation to the subject). Participants were left alone in the room while they were describing the objects.
2. *Powerwall* (i.e., 3D immersive visualization) condition: participants interacted with 3D digital copies of objects visualized in an immersive stereovision system (see Figure 2). The Powerwall is a retro-projected surface of 4:56 m by 2:25 m illuminated by twelve projectors (each 1024 × 768 at 60 Hz) with circular passive polarization filters. The projectors are connected to a rendering cluster of six commodity Linux-based rendering nodes (Pentium Q9550 2.83-GHz GeForce GTX 280 4-Gb

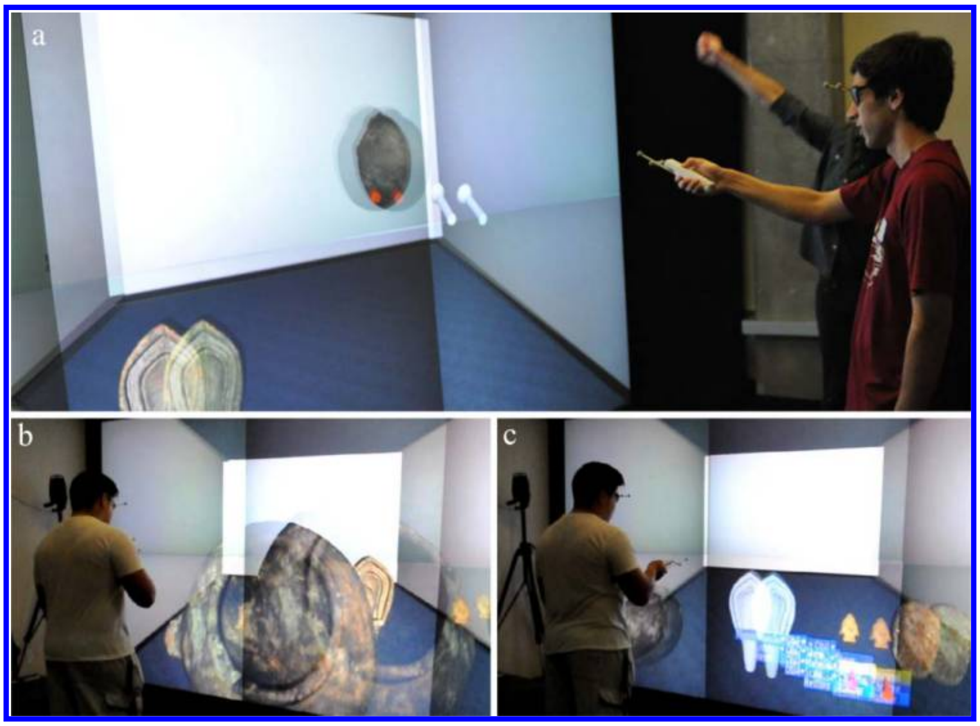

Figure 2. *Powerwall condition: (a) Changing light condition to explore objects; (b) Manipulating objects (objects appear big on the screen due to off-axis parallax projection but the user perceives it as in real-life); (c) Interacting with the objects without original colors (note the floating virtual menu in front of the user).*

RAM) driven by a similar main machine controlling the virtual scene being displayed. The dimensions of the objects and scenes are preserved and perceived by the user as in a real-life experience. The 3D digital copies were made using a Next Engine desktop triangulation laser scanner and then optimized and imported in the Powerwall framework (1.6 million triangles and 400 Mb compressed textures in total).

In this condition, participants were asked to interact with one object at a time and then, when they felt ready, to look at a camera and describe each object and then guess its function in the past. Object captions were placed on a desk close to the participant, in the same appearance order of the objects in the application. The camera was located on the right side of the Powerwall screen, about 2.0 m from the presenters. In this condition, participants had the option to manipulate the objects interactively and select specific actions through a virtual floating menu. As shown in Figure 2, the user controls a virtual pointer in the scene (red cone) directly mapped to the position in space of the remote controller. The pointer is perceived by the user as floating in front of the controller being held. The user is able to manipulate each object by selecting it with the virtual pointer, similar to real-life manipulations (see Figures 2[a] and 2[b]). Through a virtual menu that can be opened and removed at will (see Figure 2[c]), two actions were possible (see Figure 3): removing original colors (i.e., *texture*) to appreciate the 3D model geometry *mesh*, and changing light conditions (environmental or torch light simulation, and light source colors). A virtual scale did not accompany the objects displayed during the experiment. After the interaction, before any other activity, participants were asked to place the controller on the desk.

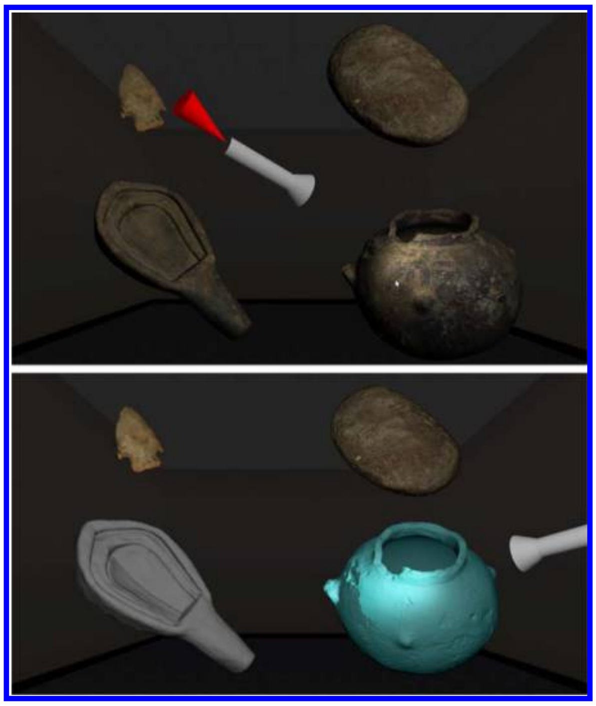

Figure 3. *Highlight of object manipulation and visualization in the Powerwall in dark environmental light condition. The red cone represents the user's pointer designed to interact with the scene (objects and menu 3D interaction and lights repositioning). Top: the user is moving the light source to enhance objects' details. Bottom: similar situation where the objects' textures were removed to analyze the polygonal representation.*

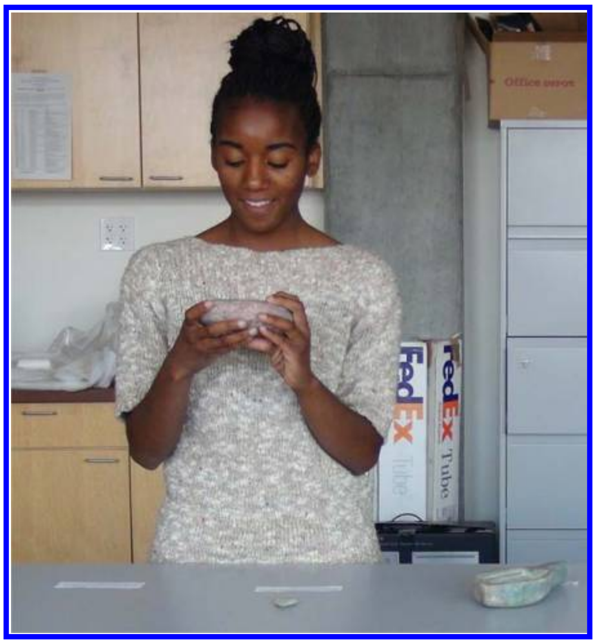

Figure 4. *Participant in the 3D prints condition.*

3. *3D prints* (i.e., 3D printed haptic) condition: participants touched 3D printed copies of the original artifacts (see Figure 4). The prints were located on a table and the caption was placed 3 cm behind them. Participants in this condition were asked to hold one object at a time in their hands and, while touching the object, describe it looking at the camera, which was on the other side of the table. While they were describing the objects, participants were left alone in the room. The 3D prints were made using a ZCorp rapid prototyping device, which allows for photorealistic, color design prints with resolution of up to 650×540 DPI. The material used is powder combined with adhesive, which are simultaneously delivered by an inkjet print head. Finally, the part can be finished using infiltrants including wax, cyanoacrylate (superglue), and epoxy materials, which increase the 3D object strength and create the desired finish to ensure durability and more vivid colors. The printed product is a hard, rigid material that is slightly delicate and not suited for structural parts under great load. While these prints can reproduce size, shape details, and color grain with a high level of accuracy, it has some known issues in the reproduction of tonality (the colors are usually faded) and is unable to reproduce the weight of original objects. Nonetheless, among the used objects, the only 3D print whose weight significantly differed from the weight of the original artifact (about three times heavier), was a Buddhist object. In this case, the original artifact is made of a considerably light type of wood.

Sixty people participated in this study (the number was determined based on previous similar studies; e.g., Klatzky et al., 1985; Lederman & Kaltzky, 1990). All were undergraduate students who received extra credit in a class. Half the participants were female. All were highly proficient English speakers with normal or corrected vision.

Participants in the Look or 3D print conditions were left alone in the lab facility, free to interact with the arti-

Figure 5. *Objects selected for the experiment: (a) Buddhist ritual object from Nepal; (b) Grinding stone from California; (c) Ceramic vessel from Ethiopia; (d) Projectile point from California.*

facts displayed, and then they completed a questionnaire to explain their experience with each object. Participants in the Powerwall condition were left alone in the Virtual Reality lab, in front of the Powerwall. After they interacted with the 3D digital replicas they completed a questionnaire to explain their experience with each object.

The questionnaires were analyzed in order to determine which type of interaction would be most suitable for research and presentation needs of the archaeological material being presented to the general public. Each participant participated in only one condition among the three that were implemented.

Four artifacts made from a range of different materials and coming from different geographic areas and chronological contexts were selected for the experiment, with the goal of evaluating to which degree the techniques of 3D scanning and printing are perceived differently for different materials (e.g., stone and pottery), shape, and other physical qualities such as weight, density, and so on. The artifacts selected were: (a) a Buddhist ritual object from Nepal; (b) a grinding stone from California; (c) a ceramic vessel from Ethiopia; and (d) a projectile point from California (see Figures 5, 6, and 7). Next we report a few of the most interesting findings we have observed in our collected data.

Figure 6. *3D prints of the objects selected for the experiment: (a) Buddhist ritual object from Nepal; (b) Grinding stone from California; (c) Ceramic vessel from Ethiopia; (d) Projectile point from California.*

3.2 Results

We conducted an analysis of responses using one-way ANOVA with the three between-subjects perceptual condition factors (individual comparisons were performed through Tukey's HSD and Bonferroni tests). The ANOVA analysis compares mean differences among three or more experimental conditions. In this experiment, the null hypothesis states that the means of all conditions are not statistically different from one another. The null hypothesis is rejected when at least one of the means being compared is significantly different from the others, which is indicated by a resulting p-value of less than .05. We used one-way ANOVA for each of the following questions (see Figure 8 and Table 1 for mean values and standard deviations).

Q1. How heavy is this object compared to an apple? (Likert scale with 1 being "very heavy" and 9 being "very light")

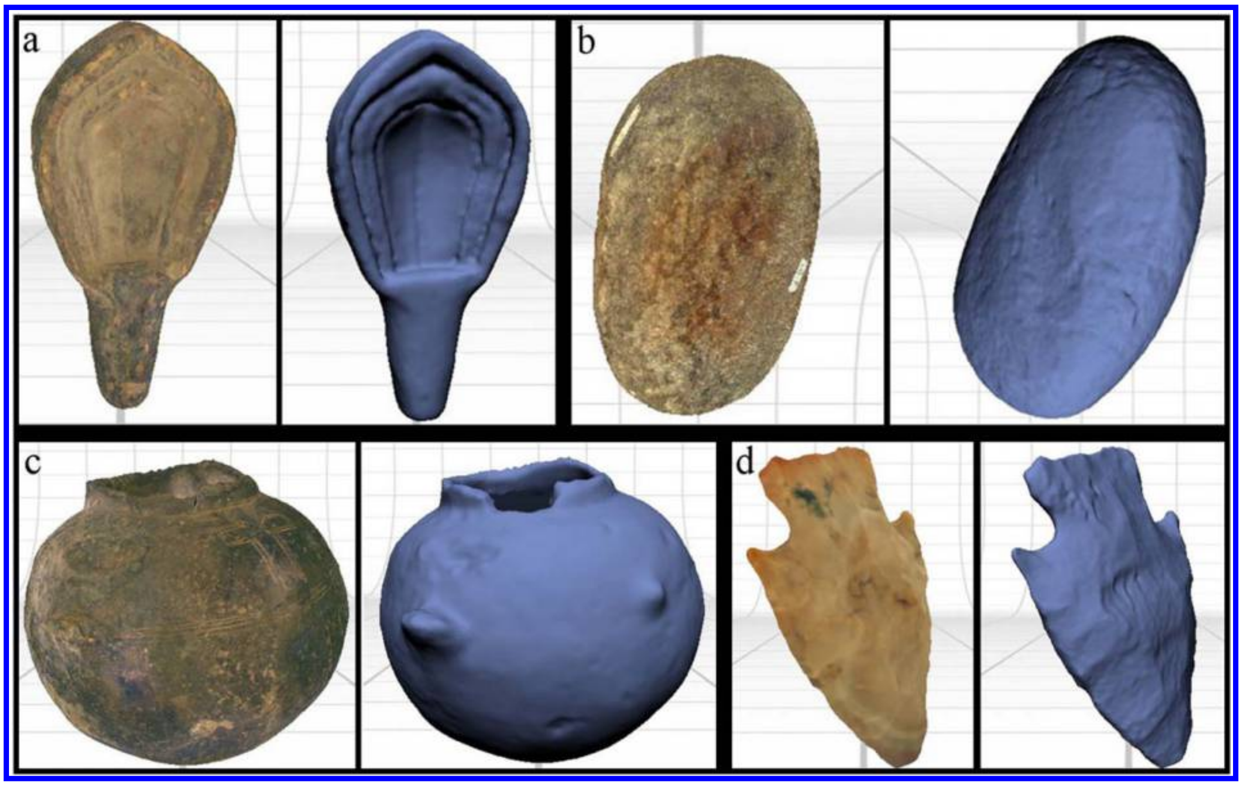

Figure 7. *3D virtual reproductions of the objects selected for the experiment: (a) Buddhist ritual object from Nepal; (b) Grinding stone from California; (c) Ceramic vessel from Ethiopia; (d) Projectile point from California.*

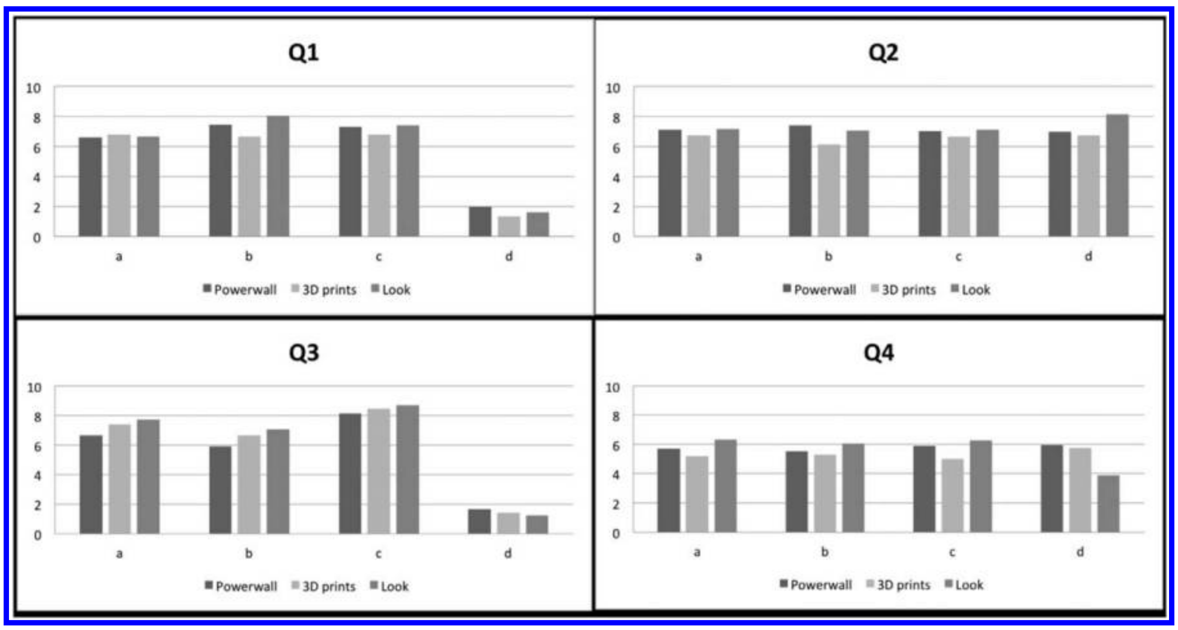

Figure 8. *Graphic representation of Table 1.*

Table 1. *Mean Values and Standard Deviations of the Likert Scale Questionnaire (a. Buddhist Ritual Object; b. Grinding Stone; c. Ceramic Vessel; d. Projectile Point)*

Conditions							
Questions		Powerwall		3D Prints		Look	
		M	*SD*	*M*	*SD*	*M*	*SD*
Q1	a	6.6	1.63	6.8	1.61	6.65	1.63
	b	7.45	2.01	6.65	1.35	8.05	.94
	c	7.3	1.56	6.8	1.76	7.4	1.76
	d	2.0	1.17	1.35	0.49	1.6	1.09
Q2	a	7.1	2.02	6.75	2.17	7.15	2.03
	b	7.4	2.04	6.15	2.54	7.05	2.63
	c	7.0	2.34	6.65	2.41	7.1	1.97
	d	6.95	1.67	6.75	2.09	8.15	1.53
Q3	a	6.65	1.09	7.4	1.14	7.7	1.08
	b	5.9	1.68	6.65	1.14	7.05	1.05
	c	8.15	0.99	8.45	0.76	8.7	0.80
	d	1.65	1.04	1.4	0.59	1.25	0.55
Q4	a	5.7	2.11	5.2	1.61	6.35	1.76
	b	5.55	2.66	5.3	2.05	6.05	1.7
	c	5.9	2.75	5.0	2.38	6.3	2.41
	d	5.95	2.42	5.75	2.19	3.9	2.59

Overall, for the case of the grinding stone, $F(2, 57) = 4.38$; $p = .017$, participants in the 3D prints condition perceived the objects heavier than participants in the Look condition. In addition, looking at the trend proposed by the other objects a similar pattern can be recognized.

Participants in the Powerwall condition perceived the objects' weights similarly, but not significantly more, than participants in the Look condition.

Q2. How easy was it to appreciate the colors of this object? (Likert scale with 1 being "very difficult" and 9 "very easy")

Participants in the Look and Powerwall conditions found it easier to perceive the colors of the objects than participants in the 3D prints condition. The difference was found significant only considering the results from the data retrieved from the projectile point, $F(2, 57) = 3.61$; $p = .034$. However, even in this case, all the means were similarly showing the same pattern.

Q3. How big is this object compared to an apple? (Likert scale with 1 being "very small" and 9 being "very large")

Participants in the Powerwall condition perceived both the Buddhist ritual object, $F(2, 57) = 4.79$; $p = .012$, and the grinding stone, $F(2, 57) = 3.91$; $p = .026$, smaller than participants in the Look condition. A similar trend can be seen considering the case of the 3D prints condition where participants also perceived both the Buddhist ritual object and the grinding stone bigger than participants in the Powerwall condition, but in this case the difference is not significant. For the ceramic vessel, a similar tendency can be seen, even though, as shown by the projectile point data, participants in all conditions selected similar values (Average: projectile point 1.2–1.7; ceramic vessel 8.1–8.7) to define the size of these objects.

Q4. What is the texture of this object? (Likert scale with 1 being "smooth" and 9 "rough")

Participants in the Look condition perceived the projectile point as significantly smoother than participants in the Powerwall and 3D prints conditions, $F(2, 57) = 4.41$; $p = .017$. This result seems to be in contrast with the tendency shown by the other two objects; nonetheless, the tendency was not statistically significant.

Conclusions are summarized in Section 6.

4 Experiment 2

In the second experiment, we have examined how people use gestures to describe objects in different modes: (1) traditional visual examination, (2) 3D immersive visualization, and (3) 3D printed replica interaction. The goal of this second experiment was to analyze when and how gestures were used in discourse about artifacts displayed in varied media.

4.1 Description of the Experiment

We had participants interacting with objects in the same conditions as described in the previous experiment: Look, Powerwall, and 3D prints. Thirty people participated in the study (the number of participants was determined based on previous studies; e.g., Matlock, Sparks, Matthews, Hunter, & Huette, 2012). All were undergraduate students who received extra credit in a class. Half the participants were female. All were highly proficient English speakers with normal or corrected vision.

Participants were video recorded during the experiments (in the Virtual Reality lab or in another lab) and before starting each activity they completed two surveys: a demographic survey (age, major area of study, etc.) and a survey about their previous experience with artifacts (real or digital). After the surveys were completed, participants were given verbal instructions and then were left alone during the experiment, in order to let them feel more comfortable in front of the camera.

Interviews were video recorded (with audio). The gestures in the videos were analyzed in order to determine which type of interaction condition is most suitable for research communication and presentation of archaeological material to the general public. Our analysis compared how participants gestured while talking about the artifacts. Gestures are believed to facilitate reasoning and learning (Goldin-Meadow, 2003; Matlock et al., 2012) and can help in describing abstract objects (Bavelas, Chovil, Lawrie, & Wade, 1992). Gesture scholars often distinguish between beat gestures and iconic gestures. Beat gestures are rhythmic hand movements that convey no semantic information, but are believed to facilitate lexical access (Krauss, 1998).

When describing an artifact, for instance, a person might make three short repeated gestures to help formulate what he or she is trying to say (e.g., shaking one hand). Iconic gestures are manual movements that convey visual-spatial information about the topic of discourse (McNeill, 2007). While describing the function of a grinding stone, for instance, a person might say, "this is for grinding corn," while making a gesture that depicts the action of grinding.

Each subject participated in only one condition. Next we report a few of the most interesting findings we have observed in our data.

Table 2. *Mean and Standard Deviation of Beat and Iconic Gestures Produced by Participants while Talking about the Artifacts*

	Beat		Iconic	
Condition	*M*	*SD*	*M*	*SD*
Powerwall	28.1	23.75	3.9	3.48
3D prints	8.1	18.42	5.9	3.51
Look	7.8	6.23	5.3	4.69

4.2 Results

Our in-depth analysis examined when and how iconic and beat gestures were used in discourse about the artifacts displayed in varied media. Table 2 shows the values for the average number of gestures produced by each group of participants in each condition.

Participants produced more iconic gestures in the 3D prints condition and fewer in the Powerwall condition, but the difference was not significant.

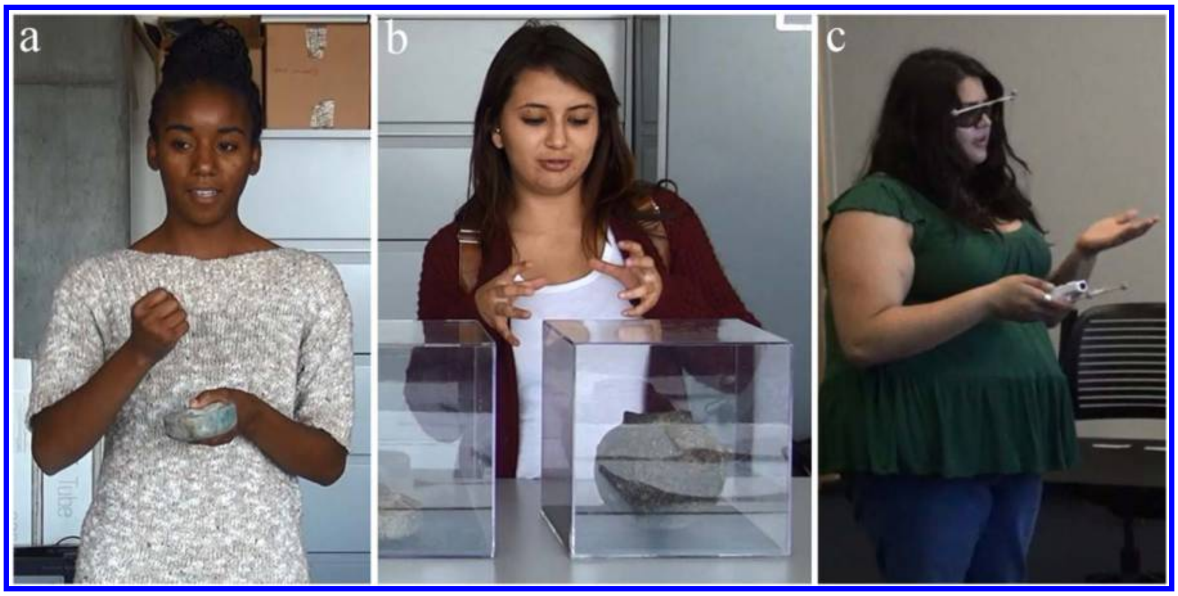

Figure 9. *Iconic gestures performed while describing the artifacts. (a) describing the function of the grinding stone (mono) in association with the Buddhist object (considered to be a metate); (b) describing the shape of the ceramic vessel; (c) defining the size of the Buddhist object (compared to a hand).*

Participants used more beat gestures in the Powerwall condition than in all other conditions. This finding was reliable when comparing Powerwall to both Look and 3D prints conditions, $F(2, 27) = 4.31$; $p = .024$.

Subsequently, we have classified types of iconic gestures used by participants while describing the artifacts. Gestures were mainly used to describe motion. Iconic gestures conveying motion were frequently used to give information about the function of an object. For instance, while talking about a projectile point, a few participants said: "It was used for hunting" and then mimicked the action of throwing a spear or dart to kill an animal. Similarly, while describing a grinding stone, some participants mimicked the circular motion performed by people to grind seeds or other vegetal foods. Gestures included describing the original context in which the object was likely used; for instance, some people visually described the shape of a metate (i.e., milling slab) in association with the grinding stone (believed to be a mono) or associated the latter to the Buddhist object, when this was believed to be a metate (see Figure 9[a]).

Participants often used gestures while talking about how the artifact was manufactured; for example, while describing the projectile point, a few participants simulated the flaking process. Iconic gestures were also used to define the shape of an object and/or stress elements of shape (see Figure 9[b]). In the case of a pot, which had a missing part of the lip and handle, gestures helped to stress the shape of the missing parts. Some participants performed iconic gestures while talking about textures and materials of an object. Iconic gestures also helped some people convey the size of an object, especially in cases where it was difficult to determine object scale (see Figure 9[c]).

A few other observations on how participants interacted with various media are in order.

All participants in the Look condition seemed more uncomfortable when interacting with artifacts than their peers in the other conditions. In viewing the objects displayed in cases, they often leaned close to examine specific details. At the same time, though, they kept their hands far from the case. Some participants put their hands behind their back, and others rested their hands on the table. Some participants shyly touched cases with their fingertips and then quickly retracted them.

Participants in the Powerwall condition could interact with 3D replicas of artifacts with the remote controller.

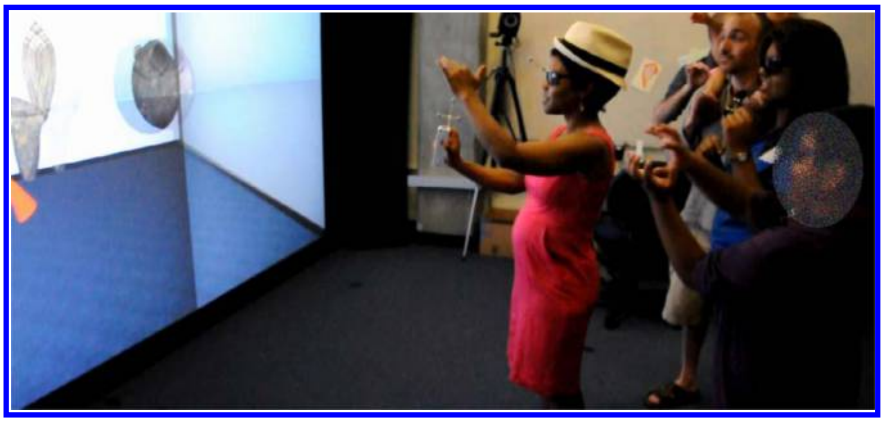

Figure 10. *Participants trying to touch 3D objects on the Powerwall (exhibition, stage 1).*

They were able to virtually manipulate the artifact before describing it, but they were asked not to touch the remote controller while talking. Observing the videos, we noticed that during the stage of interaction with the artifacts (i.e., before talking) most participants behaved as if they were touching the objects (i.e., as if the objects were "real," holding the object with the remote controller while touching it with the free hand). However, even though instructed, while talking about these objects in front of the camera, participants found it difficult not to touch the remote controller. Finally, 3D print participants interacted with 3D prints as they would with real-life objects.

For interpretations of these results see discussions and conclusions in Sections 6 and 7.

5 Experiment 3

In April 2014, we organized a one-day exhibition titled, "What are you 'Looking' at: Experiencing Ancient Artifacts." Through hands-on 3D virtual and material interaction with ancient artifacts, the exhibition was aimed at problematizing the archaeological display and showing how our perception of the past is affected by the medium used to present it.

5.1 Description of the Experiment

All participants were first brought to the Powerwall lab (stage 1), where they interacted with 3D digital replicas of artifacts through the immersive system (see Experiment 1 and Figure 10). In a second stage (stage 2), all participants were guided to another room where they saw the original artifacts displayed in glass cases and also interacted with pictures, 3D prints, and 3D digital replicas of the same artifacts displayed on a computer screen. In this room, they were free to interact with any of the media and were then asked to voluntarily participate in a questionnaire and rate (Likert scale) their overall experience with both the Powerwall and the other medium chosen (see Figure 11).

Sixty visitors agreed to participate in the questionnaire. During stage 2, just a few participants selected the 3D digital replicas on the PC (4 out of 60), while no one wanted to interact with the pictures. For this reason, the 3D digital replicas and pictures were not included in the statistical analysis related to evaluate participants' engagement with the medium.

5.2 Results

The rating scores were transformed in mean scores (see Table 3) and correlated using ANOVA statistical analysis.

We first compared all questions in order to analyze to what extent the medium helped visitors to understand the characteristics of the artifacts. Comparisons between Q1 (lights settings in the Powerwall), Q6 (tactile experience with 3D prints), and Q10 (visual experience with original objects) revealed no statistical difference among

Figure 11. *Participants interacting with original artifacts inside cases (top) and with 3D prints (bottom; exhibition stage 2).*

the three conditions. However, looking at the means, we did notice that while these values almost coincide when observing Powerwall and Look conditions, they are slightly higher in the 3D prints condition (i.e., the tactile experience was rated higher).

When comparing Q2 (removing color from digital artifacts in the PW) to Q6 (tactile experience with 3D prints), and Q10 (visual experience with original objects) a statistical difference was revealed between 3D prints and Powerwall conditions, $F(2, 54) = 3.52$; $p = .037$.

In summary, the possibility of changing light settings in the Powerwall was considered almost as useful as touching 3D prints or looking at original artifacts for the understanding of the objects' physical qualities. On the other hand, the capability of removing original colors from the 3D digital models was not considered as effective as touching 3D prints.

Second, we compared all questions in order to analyze which of the three conditions/media participants considered most helpful for understanding the artifacts (Q3, Q7, Q11). Statistical analysis showed no reliable difference among the three conditions. However, the mean values for Powerwall and 3D prints conditions were higher, suggesting that these conditions were considered slightly more helpful than Look to appreciate the artifacts.

Third, comparing questions aiming at rating the overall effectiveness of each medium (Q4, Q8, Q12), we did not find any reliable difference. However, on average the Powerwall and 3D prints were considered slightly more effective than Look to interact with ancient artifacts.

Finally, when comparing all questions aimed at rating engagement within each condition, we found that the Powerwall and 3D prints conditions were considered significantly more engaging than the Look condition, $F(2, 54) = 8.58$; $p = .001$.

The questionnaire ended with a multiple-choice question in which we asked participants to compare the experience they had with the Powerwall with the other condition they selected during stage 2, and an open-ended question in which we asked them to explain why they preferred a particular experience. As mentioned before, pictures and 3D replicas on a PC screen were not included in the analysis, since just a few participants interacted with these two media (3D digital copies on a PC: 4 out of 60; pictures: 0). It is interesting to notice that three out of the four participants who interacted with the 3D digital copies on the PC screen preferred the Powerwall experience and one was neutral.

Comparisons between Powerwall and the remaining conditions (Look and 3D prints) revealed that participants interacting with original artifacts exhibited in glass cases preferred the experience with the Powerwall, X^2 $(2, N = 18) = 2.12$, $p = 0.03$. Most of the participants who expressed their preference for 3D prints and Powerwall explained that these experiences were more engaging because they could touch (i.e., with the

Table 3. *Likert Scale with 1 Being Strongly Disagree and 9 Being Strongly Agree*

Questionnaire Experiment 3		
Powerwall	Mean	*SD*
Q1. *The possibility to select appropriate lights improved my understanding of the artifacts' characteristics.*	7.45	1.54
Q2. *The possibility to remove original colors of the artifacts improved my understanding of the artifacts' characteristics.*	6.5	2.37
Q3. *The ability to use the Powerwall (full-scale 3D screen) was very helpful compared to a traditional museum display.*	7.8	1.7
Q4. *The Powerwall system seems to be a good approach to interact with ancient artifacts.*	8.2	1.11
Q5. *This experience with 3D digital artifacts was engaging.*	8.9	.31
3D prints		
Q6. *The possibility to touch 3D printed artifacts improved my understanding of the artifacts' characteristics.*	8	1.08
Q7. *The ability to interact with 3D printed artifacts was very helpful compared to interacting with 3D digital artifacts in the Powerwall.*	7.6	1.5
Q8. *3D prints seem to be a good approach to interact with ancient artifacts.*	8.05	1.05
Q9. *This experience with 3D prints was engaging.*	8.3	.86
Look		
Q10. *The possibility to look at original artifacts through a display improved my understanding of the artifacts' characteristics.*	7.47	1.74
Q11. *The ability to look at the artifacts was very helpful compared to interacting with 3D digital copies in the Powerwall.*	6.64	1.98
Q12. *Traditional display seems to be a good approach to interact with ancient artifacts.*	7.35	2.12
Q13. *This experience with original artifacts was engaging.*	7.12	2.20

3D prints) or "almost" touch the objects (i.e., in the Powerwall).

6 Discussion

The presented studies investigated how different presentation modalities influence the understanding of artifacts. We were especially interested in how people would interact, understand, and describe ancient objects in three different conditions: visual experience with authentic artifacts, 3D digital reconstructions in the Powerwall, and manipulation of 3D prints.

The results from our experiments show how the different presentation modalities affect the perception of different characteristics of the objects. With respect to weight information, our findings show that, in an immersive 3D reality situation, participants perceive objects' weight similarly to what people would perceive in a museum (i.e., looking at original artifacts located in a case). In both cases the weight estimation relies on purely visual cues that, in our opinion, would force the participant to think about the original material more carefully. Moreover, similarly to the discussion presented by Heineken and Schulte (2007), immersive VR systems expose users to visual cues that make it difficult to estimate the weight of an object. In the VR medium the weight estimation is similar to the real-looking scenario. Using 3D prints, the participant may have based his or her judgment on the actual weight of the object held. However, because of the unavailability of the original artifacts, we could not compare the weight estimation of the three media with an estimation of the weights from the originals.

With regard to color information (color grain, variation, and tonality) of the artifacts selected for the experiment, the Powerwall and Look conditions give a similar level of perception, indicating the ability of the Powerwall system to display this kind of information well. This finding is reinforced by the fact that participants in Experiment 2 indicated light variation as an effective means to perceive and understand the artifacts.

With respect to size, the Look, Powerwall, and 3D prints conditions show very similar results for both the ceramic vessel and the projectile point, which have a size not at all close to that of the reference object (an apple). For the grinding stone and the Buddhist objects, whose size is close to that of an apple (i.e., apple: given reference point for the experiment), our statistical analysis shows how these two objects were considered significantly smaller in the Powerwall than in the Look condition. This finding reinforces the idea that distance and size misestimation in immersive virtual environments is higher than in real scenarios (Naceri, Chellali, Dionnet, & Toma, 2009; Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, & Beall, 2004), even for virtual reconstruction of archaeological objects.

Regarding texture qualities, the projectile point is the only one of the objects used for the experiment for which we found a reliable difference when we compared participants in the Powerwall and 3D prints conditions to participants in the Look condition. The latter participants, in fact, perceived this object as considerably smoother than their peers in the other two conditions. Our findings suggest that in the presence of small, bright, and light-colored objects, visual cues are not enough to accurately perceive texture qualities. Based on this finding, while participants in the Look condition could grasp the sense of texture of the objects based only on visual cues, participants in the Powerwall could rely on multi-visualization tools, such as different light settings and the possibility to zoom in and remove original colors from the 3D models, to grasp textural information. To reinforce this statement we found that more than one participant stressed the importance of removing colors and changing light settings for perceiving texture qualities. One participant said: "…watching the chrome object [i.e., object without original colors], I was able to see different, other details that I was not able to see with the original colors."

The qualitative analysis of gestures (Experiment 2) shows that, in the absence of a tactile experience, people produce some stereotypical iconic gestures to mimic the actions they would perform if they were actually touching the artifacts. The iconic gestures performed often convey spatial information; they help people mimic object manufacturing and function. Gestures can also be used to describe details of shape and also help people figure out the size of an object.

As noted, when people described objects they also produced beat gestures (which do not convey any meaning per se). The results of this experiment show that participants looking at original artifacts inside cases generated the fewest gestures.

Conversely, participants interacting with objects in the Powerwall used the highest number of beat gestures. The high number of beat gestures was reliably different from the number of gestures produced by participants in the Look and 3D prints conditions. The difference with the 3D prints was not really a surprise, since participants were talking while holding the objects; thus, it was more difficult for them to perform gestures. What is more surprising is the difference between the Look and Powerwall conditions. In both cases participants had their hands free while talking. It is possible that these cases represented a psychological barrier that inhibited participants' direct experience with the objects. This idea is reinforced by the fact that, when they interacted with these objects, they kept their hands far from the case (i.e., they seemed afraid of touching it) (see Figure 2). Conversely, following Krauss (1998), who argued that beat gestures often facilitate lexical access, it is possible that the high number of beat gestures reflects a lack of certainty about artifact details. That is, participants were less certain about what they were talking about, but it might also indicate that in the immersive system participants recognized a difference, a frame, between the physical and the virtual world and tried to fill this gap using gestures. Another possible explanation, which would need further analysis, might be linked to participant engagement while interacting with the Powerwall, as demonstrated by the results of Experiment 3. In that case the high number of beat gestures might be directly correlated with the excitement people had while interacting with the objects in the Powerwall.

Experiment 3 was mainly designed to collect metacognitive information on how useful the participants considered each experience for the perception and understanding of the proposed artifacts, and how engaging they found the experience with each condition. Overall, the Powerwall and 3D prints conditions were considered more helpful and more engaging than the visual experience with real artifacts.

7 Conclusions

We present in this paper the results obtained with three experiments designed to improve our understanding of how people interact, perceive, and engage with ancient artifacts in different media states. Our results demonstrate the potential of new technologies and help design best practices and design choices for improving displays in museums and other exhibitions.

Results from Experiment 1, which focused on the perception of specific characteristics of ancient artifacts in different media states, revealed that the media selected for the experiment affect the perception of physical qualities of artifacts in different ways. The immersive experience with the Powerwall and visual experience with original artifacts resulted in similar perception patterns for color and weight, while these characteristics are difficult to perceive with the 3D prints. As a result, the misinterpretation of weight and color might also lead to misinterpretation of other qualities (e.g., material) and of the function of the artifacts. While experiencing the objects in the Powerwall resulted in size misinterpretation, it was a useful way to recognize texture qualities, especially for small and bright objects.

Results from Experiment 2, aimed at investigating how we describe and interact with ancient artifacts through our body, suggests that traditional museum settings may diminish or limit the degree of engagement with ancient artifacts.

This latter finding seems reinforced by the results of Experiment 3, which give us insights into people's engagement with artifacts through different media. These results suggest that, in the absence of a tactile experience with the original artifact, our sample of participants favored a tactile or semi-tactile experience with replicas to the visual experience with original ancient objects. In other words, these participants were ready to negotiate with the inauthentic in order to have a tactile embodied experience.

Even though some of these results might seem obvious to scholars who design and test immersive systems, they can be noteworthy to scholars in the heritage, archaeology, and museum domains. This is because ancient artifacts represent a unique type of objects, which carry information about past cultures. Thus, we expected that authentic artifacts displayed in a case would trigger "emotions" that 3D copies (virtual and real) could not equal. On the contrary our findings show that the Powerwall and 3D prints conditions were most appreciated, suggesting that our sample of participants are more concerned with experiencing an object through the senses rather than having the original in front of them. Similar findings have been reported by other studies (Michael, Pelekanos, Chrysanthou, Zaharias, Hdjigavriel, & Chrysanthou, 2010; Wrzesien & Raya, 2010; Pujol & Economou, 2009, 2007).

Our findings suggest to reconsider how we approach museum displays today, since our exhibit visitors seemed to choose an active experience with the past, which emphasizes a kinesthetic engagement with the traditional museum environment. These findings also suggest that although new technologies are not yet able to fully reproduce the perception that people would have manipulating original artifacts, these technologies produce excitement and engagement, encouraging curiosity, attention, and desire for knowledge about past material culture.

Our study represents a starting point for the creation of a protocol or methodology that envisages the integration of different technologies within a museum. It would be interesting, for instance, to see what happens to perception, engagement, and understanding when visitors interact with an object in a 3D immersive environment, or through a 3D print first, and then visit the showcase in which the original counterpart is showcased.

In summary, our paper shows that people like to engage with new technologies to understand ancient artifacts and points to the integrated use of traditional displays, 3D immersive systems, and 3D prints as an effective way to increase perception, understanding, and engagement with artifacts, as well as favoring a diverse population of museum visitors.

While our current work uncovers some first observations in this area, there is plenty of further development worth exploring. It would be critical, for instance, to investigate what may be the influences (ethnicity, gender, education, socio-economic background) in varying perceptions of authenticity in relation to objects, virtual and real. It would also be important to investigate how these results might vary across cultures, and how people with particular affiliation with tangible heritage might interact with both authentic objects and their reproductions in different media states. To this purpose, our future research will aim to expand this study by analyzing a larger sample of participants and how they interact with both virtual and 3D printed replicas in real museum settings.

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