Evaluating Learning with Tangible and Virtual Representations of Archaeological Artifacts

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ABSTRACT
Technological advances offer new methods of representing physical objects in tangible and virtual forms. This study compares learning outcomes from 61 students as they interact with ancient Egyptian sculptures using three increasingly popular educational technologies: HoloLens AR headset, 3D model viewing website (SketchFab), and plastic extrusion 3D prints. We explored how differences in interaction styles affect the learning process, quantitative and qualitative learning outcomes, and critical analysis.

Author Keywords
Augmented Reality; 3D Models; 3D Printing; Archaeology; Object-based learning.

ACM Classification Keywords
• **Human-centered computing~Mixed / augmented reality** • *Human-centered computing~Gestural input*

INTRODUCTION
Emerging technologies, such as virtual and augmented reality (AR), wearable computing, and digital fabrication, have improved the engagement and experiences of learners in a wide range of content domains [3, 22, 31]. In particular, these technologies pose unique opportunities for enhancing object-based learning. Object-based learning places interaction with physical artifacts in a central position in the learning process [55].

Disciplines that use physical artifacts for their base of analysis include anthropology, archaeology, art history, classics, and museum studies. Traditional learning paths in these disciplines do not often afford students the opportunity to engage directly with authentic objects until they have reached advanced stages of instruction. First, access to authentic artifacts is limited by the availability of museums and cultural institutions in the region of instruction. Furthermore, most museum visits do not offer opportunities for students to interact directly with artifacts, engaging with objects on a deeper level.

AR technology allows for virtual objects or superimposed information to appear as if they coexist with the real world [2]. As such, it enables educators to bring digital representations of artifacts into the classroom, and allows students to explore these objects while present in the class and in conversation with peers and instructors. However, current AR applications utilize tablets and phones, providing only limited interactions through on-screen touch gestures. The increasing availability of wearable AR devices, such as the Microsoft HoloLens headset [35], provides opportunities to develop AR experiences in which users can see and interact with digital representations of artifacts without holding an additional mediating device.

Advances in 3D scanning and fabrication technologies allow educators to engage students in exploring virtual or tangible replicas of original artifacts. Several museums, including the British Museum and the Smithsonian Museum, released 3D models of important artifacts, making them available freely for educators and the public. These digital replicas could be explored using direct manipulation interfaces (e.g. SketchFab). Alternatively, models could be 3D printed so that users can explore physical replicas of the original artifacts using tangible interaction.

However, when considering the use of such emergent technologies for fostering object-based learning, important questions include: How do differences in interaction styles affect learning process and outcomes? How does close examination of virtual vs. tangible replicas support learning? We are interested in three interaction styles along the tangible-virtual continuum: physical interaction with tangible representations (3D prints), direct manipulation interaction with virtual representations (SketchFab), and gesture-based interaction with virtual replicas (HoloLens application). We selected to study these particular interaction styles because of their increasing availability for higher education [22].

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To address these questions, we conducted a comprehensive user study with 61 adult learners, which integrates quantitative measures and qualitative indicators to explore whether and how the above three interaction styles augment object-based learning. Our findings indicate that interaction style has significant impact on various aspects of object-based learning with digital replicas. In particular, we found that the gesture-based interaction with virtual replicas (implemented on the HoloLens AR headset) was superior in terms of the learning process - demonstrating higher levels of enjoyment and reported strengths. The AR headset also showed positive effects on learning outcomes that were comparable to the on-screen interaction (SketchFab), but superior to the 3D prints. The paper continues with background and related work followed by experimental design, methods, and findings.

BACKGROUND AND RELATED WORK

Object-Based Learning

Object-based learning is a pedagogy that views direct interaction with physical objects as central for learning. The immediate goals of object-based learning are for students to practice close observation, determine what set of information to collect for research, and to build critical thinking skills for comparing and contrasting examples [55]. Learning begins with a base of direct observation and leads to higher-level interpretation. Students are expected to build their observational skills to produce comprehensive and detailed descriptions of objects, which can then be used to interpret social, political, and/or historical trends. These skills are developed by interacting with a set of artifacts. The goals of object-based learning are also related to active and experiential learning. These pedagogies view hands-on engagement with artifacts as central to constructing meaning and internalizing new concepts [55].

A large body of research in cognitive sciences and museum studies demonstrates that the manipulation of physical objects promotes understanding and learning, and even benefits mental and physical health. By manipulating an object, a student builds a mental conception through testing and observing its characteristics and relationships with other concepts [26, 27]. Object handling has traditionally been used for young students and public engagement, but pedagogical research suggests that creatively expanding its use in higher education has positive results [18]. As viewers interact with objects they make emotional associations with remembered experiences, which has been found to have positive effects on mental and physical health, both in tangible [11, 12] and virtual [34] forms.

In this study, the experience of interacting with a set of artifacts was emulated using three different, increasingly available, digital means of artifact reproduction: 3D printed physical objects, on-screen 3D models, and head-worn AR display visualization. Each modality offers different potential benefits to achieving learning outcomes: physical 3D prints provide multi-sensory input allowing students to touch and manually manipulate objects in literal hands-on learning, on-screen 3D models offer a high degree of realism as well as the ability to zoom and spin visual representations without physical constraints and with familiar control features, and head-worn AR devices provide a fully visually immersive environment that replicates the scale and presence of the object. To our knowledge, this is the first study to compare the learning outcomes achieved with these three technologies.

Learning with Physical Models

Much research indicates that tangible user interfaces can enhance learning and problem solving [1, 32, 43]. However, in this study, we focus on tangible interaction with fabricated physical models that are not augmented computationally. Research has shown that scientists often employ external artifacts to support their reasoning while tackling complex problems [40, 41, 46]. A known example is the model of DNA built by Watson and Crick, which enabled them to form and test hypotheses about the double helix structure. Research has shown that physical models can augment cognitive processes by facilitating both conceptual and material manipulation [4].

Several studies compare the use of fabricated physical objects to on-screen or paper-based interaction, demonstrating that physical objects provide cognitive support and improve information retrieval [21], as well as positively impact memorability [13, 24]. However, other studies did not find clear differences between physical and digital modalities [29, 33, 54, 58]. Additional research is needed to better understand the impact of physical educational materials on learning.

In addition, as makerspaces and 3D printing become more accessible and common in educational settings, students and teachers are able to not only use physical learning materials but also to easily produce their own physical artifacts. However, the majority of the literature that addresses the pedagogical use of 3D printing focuses on the design and production process rather than the end use [6, 10, 15-17, 19, 30, 42, 47, 48].

In this study, we evaluate the potentials of using 3D prints in the classroom, which can reflect on the *end use* of digital fabrication. Additionally, we chose to contrast the learning goals achieved through tangible models with virtual modalities that could offer their own pedagogical benefits.

Learning with AR

Recent studies comparing the use of AR and traditional content within the classroom found that AR positively affected learning outcomes. In one case, students responded positively and preferred to use AR platforms over traditional PC-based interfaces [23]. Additionally, using AR to provide the opportunity to manipulate objects that were otherwise difficult to visualize was found to significantly improve learning outcomes [14]. Comparative studies have found that AR platforms promote group collaboration over traditional media [36]. As the rapidly-expanding body of literature on pedagogical use of AR suggests a variety of benefits, there is a need for further research to discern how specific qualities of AR support cognitive, collaborative, and situated learning [9].

On a logistical level, AR holds many advantages in an educational setting, such as flexible access for otherwise limited lab hours and spaces and allowing for collaboration between remote groups [8]. Teachers and students are also able to create experiences that would be otherwise physically impossible, such as moving celestial bodies [14], building complex interactive artwork [9], or effortlessly manipulating massive sculpture as in the study we present in this paper. As AR connects virtual content with real world spaces, it offers an additive synergy that goes beyond the potentials of using either alone [8]. The "infusion" of digital content bridges between virtual and authentic experiences, potentially affording the maximum benefit of each [9]. In courses in the Humanities and Social Sciences, dialogue about different perspectives and interpretations is often as important as absorbing content. AR technology maintains interactivity with instructors and peers while viewing virtual objects, versus the completely immersive VR headset experience.

This study is motivated by these larger discussions on how visualization, connection, and engagement promote object-based learning outcomes. We explore this promise by investigating the differences in experience and in learning outcomes between physical interaction with 3D prints, direct manipulation of on-screen 3D models, and gestural interaction with virtual objects using an AR headset. Each modality offers different strengths in tangibility, flexibility of manipulation, and immersion, respectively.

Emerging Technologies for Cultural Heritage

Technological advances offer opportunities for enhancing museum visitors' interaction with cultural heritage [44, 51]. However, these opportunities also pose new challenges for curators and educators as hand-held screens and digital kiosks often distract visitors from viewing the artifacts [44].

Emerging interactive technologies also provide curators and educators with new ways to engage learners with cultural heritage artifacts outside of the museum environment. 3D scanning and 3D printing are increasingly used in archaeology and anthropology to capture representations of authentic artifacts [50]. Prominent institutions including the British Museum (used in this study), the Smithsonian Museum, and the Google Cultural Institute made scans of important cultural heritage pieces available to educators and to the public [28, 38]. There are many advantages to using 3D scanning in the museology and archaeology fields, including capturing details, preservation, replication, and broadening access. However, 3D printed replicas, in plastic or other materials, might lose the authenticity of the original object. This concern is echoed by curators in regards to digital replicas [44]. This study provides new insights into the strengths and weaknesses of digital vs. physical 3D printed replicas.

STUDY

Goals and Research Questions

The goal of this study is to investigate whether and how different interaction styles with physical and virtual replicas augment object-based learning. In particular, we explored the following questions: 1) How do differences in interaction styles affect the learning process (time on task, perceived workload, spatial presence, and attention allocation)? 2) How do differences in interaction style affect quantitative and qualitative learning outcomes? 3) How does close examination of virtual vs. tangible replicas support visual and critical analysis?

Experimental Task

The study task was adapted from an archaeology class, where it was applied to help students develop their visual observational skills and to hone their critical analysis. The task involves selecting two artifacts from an available inventory with six artifacts, exploring them, and completing the respective object questionnaire. For each object, participants were asked to state the first detail they noticed, all the details they noticed, and what seemed to be unique or similar about the object compared to the rest in the set.

Experimental Design

We used a between-subjects design across three conditions. We chose to compare interaction styles along the tangible-virtual continuum: physical interaction with tangible replicas (3D prints), direct manipulation interaction with virtual replicas (SketchFab), and gestural interaction with holographic replicas (HoloLens application). These interaction styles were selected because of the increasing availability of their underlying technologies for educational settings [22]. We chose a between-subjects design in order to balance a meaningful object-based learning activity with a reasonable (less than 1 hour) session duration. Participants were randomly assigned to one of the following conditions:

3D prints

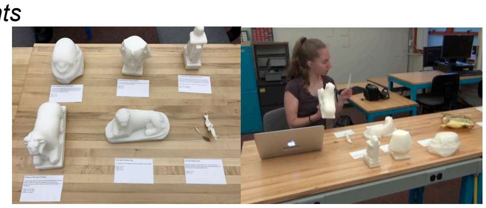

Figure 1. 3D Prints artifact inventory (left) and participant exploring and reading about the selected 3D print (right).

This condition presented participants with 3D printed replicas of six artifacts, produced using scans provided by the British Museum of 42k – 1.1M faces and 23.9k – 529k vertices and printed through the MakerBot Replicator 2X and Afinia H800. All models were printed using either PLA or ABS Natural filament. The 3D models were printed at the highest resolution and largest size possible, while retaining correct between-model scale. We chose to use 3D printers that are currently available in many educational spaces. Descriptions of the artifacts were presented using printed cards set next to each artifact (Figure 1). Participants could pick up an object and explore it tactilely.

SketchFab

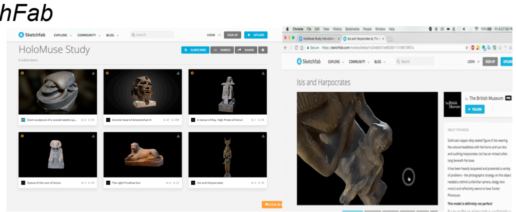

Figure 2. SketchFab artifact inventory (left) and artifact selected and being explored in SketchFab condition (right).

This condition presented participants with an inventory comprising of 3D scans of six artifacts through the online 3D modeling desktop platform, SketchFab (Figure 2). Participants could select an artifact and explore it using the mouse and a direct manipulation interface. The platform also presented a description for each artifact.

HoloMuse

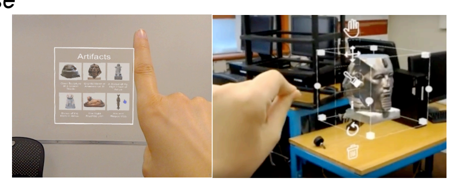

Figure 3. Holographic artifact inventory (left) and participant rotating the selected holographic artifact (right).

In this condition, participants used HoloMuse [45], a Microsoft HoloLens AR application developed using Unity and C#, which presents users with an inventory comprising of six holographic artifacts (Figure 3). Participants could select an artifact and explore it by moving, rotating, and scaling the artifact using in-air gestures. Participants could also show or hide the artifact's material to see its surface, and display additional information about the object.

Throughout all conditions, the artifact inventory, artifact order, artifact descriptions, and settings were consistent.

Procedure

Participants signed a consent form and then filled a pre-task questionnaire, providing demographic information, specifying their prior experience with visual analysis (e.g. art history class), and reporting prior experience with AR, VR, and 3D modeling software. Participants were then shown an artifact inventory of six models and given training on how to select an artifact and manipulate it.

Following this training, each participant was given the task of exploring two objects of their choice and completing an object questionnaire for each using a laptop we provided. Following the completion of the task, each participant completed a post-task questionnaire with 15 Likert-type questions, each rated on a 5-point scale from "Strongly Disagree" to "Strongly Agree" (Table 4); a NASA TLX questionnaire [19, 39]; and four open-ended questions about the platform. Participants in the HoloLens condition were also asked whether they experienced a headache or discomfort while wearing the device. Throughout each section of the study, participants were not limited in time. We collected data through questionnaires, application logs, and video recording of the session.

Measures and Indicators

In order to evaluate the following measures and indicators, we collected both quantitative and qualitative data which were assessed through standardized enjoyment and workload metrics, as well as content-specific coding developed in consultation with a domain expert:

Time on task

We explored the effect of interaction style on total time on task as well as on the time spent exploring selected objects. In this study, time on task was not used to deduce efficiency, but rather to deduce meaningful engagement.

Enjoyment

We also asked participants to rate their level of enjoyment using the interface. We used a Likert scale of 1 to 10 from low enjoyment to high enjoyment.

Perceived task workload

We measured users' perceived task workload with the NASA TLX questionnaire [18]. We interpret the results of the unweighted, raw NASA TLX data, grouped by category (i.e. frustration, effort, mental demand, physical demand).

Spatial presence

We measured users' perceived spatial presence with a series of questions loosely based on the MEC-SPQ standardized questionnaire [56], which consists of eight dimensions. Table 4 shows question content and results by condition.

Learning outcomes

The qualitative assessment of learning outcomes was based on insight-based evaluation methodology [48], and was developed in consultation with a domain expert, who drew on their 15 years of experience in teaching and assessing learning outcomes in related content at the university level. We analyzed the open response questions about the viewed artifacts, such that for each response, we derived the number of words, number and type of concepts referred to, and the level of analysis. The concept codes used were selected to demonstrate desired progression from observation to interpretation. Participants were expected to produce comprehensive and detailed descriptions of objects, which can then be used to interpret social, political, and/or historical trends. The content codes were developed in consultation with the domain expert, and after an initial round of coding were condensed into more general categories. We used the following codes: *Visual inspection* - shape, color, and texture; *Complex visual observation* - damage, detail, and facial feature; *Inferences* - material, size and weight; and *Interpretation* - aesthetic, analysis, and context. In addition, the domain expert co-author assigned the open responses from each participant a score between 1-5 based on complexity and on cognitive engagement with the artifacts. We used the following classification, which is based on Bloom's taxonomy [7]: Score 1 - Response was brief and included a single descriptive observation; 2 - Response was brief and included several descriptive observations; 3 - Response was short to medium length and included several descriptive observations, and at least one critical or comparative assessment of the object; 4 - Response was medium length and included more critical or comparative assessment than descriptive observation; and 5 - Response was medium to long and was primarily critical or comparative assessment.

Post-task

Finally, we asked participants about the *strengths and weaknesses* of viewing and learning about an object using the interface they interacted with.

Data Analysis

Quantitative data was analyzed using IBM SPSS Statistics, Version 24. Mean comparison was conducted using ANOVA. Post hoc differences between conditions were analyzed with Tukey tests. Responses to open questions were analyzed using content analysis methods. First level codes were developed from preliminary review of the data by the content domain expert. Two independent coders were trained to code the data, and thematic categories were identified and analyzed (see table 3). After an initial coding of 10% of the data, the coders discussed inconsistencies in their codes and calibrated. The final inter-coder reliability based on all the data was excellent with agreement >95%.

Participants

We recruited 61 participants, all students and recent graduates (42 female, 16 male, 3 not specified; age M=20.9 SD=2.5). Each participant was randomly assigned to a condition; however, we did balance for gender. We found no significant differences based on self-reported experience with visual analysis or 3D interaction (AR or VR). All participants completed the study, and were compensated with a $10 gift card.

RESULTS

	3D Prints	SketchFab	HoloLens
N	20	20	21
Female	14	14	14
Male	5	5	6
Not specified	1	1	1
Minutes on task	20:05 (4:32)	23:51 (7:34)	32:30 (6:40)
Minutes on objects	10:48 (3:04)	13:52 (5:41)	12:35 (4:34)
Enjoyment	6.05 (2.14)	6.70 (1.42)	7.52 (2.16)

Table 1. Gender distribution, and mean and standard deviation for time spent on the entire task, time spent investigating the objects, and enjoyment, by condition.

Time on Task

Time spent investigating objects, and total time spent in each condition can be found in Table 1. There was a significant effect of condition on total time spent on the task [F(2,58)=20.397, p<.001]. Post hoc comparisons indicated that the average time spent in the HoloLens condition was significantly different than the time spent in the other two conditions. However, there was no significant effect of condition on time spent investigating the two selected objects [F(2,58)=2.555, p=.086].

Enjoyment

Enjoyment scores for each condition can be found in Table 1. There was a significant effect of condition on enjoyment [F(2,58)=2.974, p= .047]. Post hoc comparisons indicate a significant difference in enjoyment between the HoloLens and 3D prints conditions.

Perceived Task Workload

There was a significant difference in the perceived physical workload between conditions [F(2,58)=6.103, p=.004]. Post hoc comparisons indicated that the mean score for the HoloLens condition (M=4.76, SD=2.45) was significantly different than the 3D prints (M=2.40, SD=1.87) and SketchFab conditions (M=3.05, SD=2.35). There were no other significant differences. Figure 4 shows NASA TLX dimensions per condition.

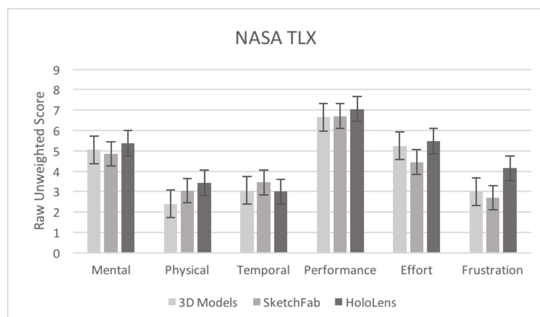

Figure 4. Average unweighted NASA TLX scores and standard error bars by condition.

Learning Outcomes

We evaluated learning outcomes in terms of number of words of the open responses, number and content of thematic codes, and a complexity score assigned by a domain expert. Table 2 includes the word count, number of themes mentioned, and complexity scores for task questions. There was no significant difference in the combined complexity score across conditions.

However, for the question asking participants to list all details noticed about an object (see Table 2), the number of thematic codes appeared in the responses was significantly higher in the HoloLens and SketchFab conditions as compared to the 3D prints condition.

Looking at the frequency of specific thematic codes (see Table 3), we found the following significant differences. Material was mentioned significantly more in the SketchFab and HoloLens conditions, as compared to the 3D prints condition. Facial features were mentioned significantly more in the 3D prints condition as compared to the HoloLens condition. Color was mentioned significantly more in the HoloLens condition, as compared to the 3D prints condition. Lastly, context was mentioned significantly more in the SketchFab and HoloLens conditions, as compared to the 3D prints condition. There was also a significant difference in the number of users who mentioned size in response to the question about selecting a favorite object and explaining why, between the Sketchfab (0/20) and HoloLens (7/21) conditions and the 3D prints (5/20) and SketchFab, but not between the HoloLens and 3D prints conditions.

There was no significant difference found in the number of codes used, word count, or complexity score for self-reported "Experts" and "Non-Experts" in visual analysis.

Thematic code	3D Prints (N=20)	SketchFab (N=20)	HoloLens (N=21)	F	*p*
texture	7	12	11	1.308	.278
material	7	16	16	6.287	**.003**
detail	19	20	20	.488	.616
facial feature	19	14	10	6.422	**.003**
color	6	13	14	3.741	**.030**
damage	9	10	15	1.657	.200
size	12	8	14	1.591	.213
analysis	11	15	16	1.327	.273
weight	1	1	1	.001	.999
context	5	16	16	10.236	**<.001**

Table 3. Frequency of thematic codes and one-way ANOVA results.

Spatial Presence
Question content and scores by condition for the spatial presence questionnaire can be found in Table 4. Participants in the SketchFab and HoloLens conditions reported feeling that the artifact was present in their environment significantly more than the 3D prints condition participants.

Participants in the SketchFab and HoloLens conditions responded that they still maintained a concrete mental image of the artifact during the post-task at higher levels than those in the 3D prints condition. Finally, participants in the SketchFab condition reported significantly higher levels of consideration of the usage of the objects than participants in the 3D prints condition.

Object Distribution and Favorite Objects
Participants were allowed to select which objects they viewed, and later were asked to describe their favorite object. Table 5 lists the objects in the order they arranged in the inventory for participants, as well as participants' choices. In general, participants chose objects they were drawn to. When statues of animals were chosen and viewed, they had the highest frequency of becoming the participant's favorite object for the session. Viewers seem to have preferentially chosen the Right Prudhoe Lion and the statue of Isis and Harpocrates. There were no apparent differences across conditions.

Platform Strengths and Weaknesses
In the post-task questionnaire, participants mentioned significantly more strengths in the HoloLens condition compared to SketchFab. Participants also mentioned significantly more weaknesses in the 3D prints condition compared to the other two conditions.

In the 3D prints, most mentioned strengths were tactility (15/20), manipulation (7/20), and angles (7/20). As one participant stated: "You get to feel the details, see the object up close, it is easier to rotate it and look at it from all angles." Notable weaknesses were details (11/20) and colors (10/20). One participant said: "Much of the detail of the objects is taken away when you are just viewing a basic, white-colored 3-D printed replica. It's impossible to imagine the colors or the medium of the actual object." A higher 3D print resolution could change user perception of damage and details; however, since the models were printed at the highest resolution possible, these observations remain relevant.

In the SketchFab condition, the most common strength mentioned was angles (11/20). As one participant noted: "I think it was great to see all angles of the objects in views that I would not have been able to in a museum." The most common themes for weaknesses were lack of interaction (9/20) and size (9/20). In the words of one participant: "The weaknesses of exploring an object in this way is that some viewers may not feel as if they are interacting with the object." Another participant mentioned: "It is still not physically in your view and some picturing must be done in order to understand the dimensions of an object."

Finally, in the HoloLens condition, the most reported strengths include manipulation (6/21), size (6/21), scaling (4/21), and kinetic movement (4/21). In the words of one participant: "I found myself engaging with the objects in a way that I likely wouldn't have in a museum or certainly image format. The ability to manipulate the objects yourself, change their sizes and perspective, and truly interact has a certain draw." Another participant noted: "I loved being able to walk around an object in its entirety and have it to myself." Most prevalent weaknesses were: hard to use (7/21), and size (5/21). As one participant noted: "I did struggle with gauging size/scale of the objects and would have valued from some type of scale indicator. I also found that if I tried to move the objects they jumped closer to me in my range of vision and that made it more difficult for me to see and manipulate the objects." Additionally, 52% of participants (11/21) reported headache or eyestrain while wearing the device. This is a critical limitation of this device; future studies will determine to what extent the discomfort is associated with the current version of the HoloLens device.

DISCUSSION
Here we discuss our main findings from comparing learning process and outcomes across the three different conditions:

Assessing Quantitative Learning Results

Across all three conditions, there were no significant differences in the combined complexity score of participants' task responses to open questions about the artifacts they viewed. However, there were significant differences in the frequency of particular thematic codes: codes for color, material and context were notably rarely mentioned while participants viewed the 3D prints. This suggests that educators have the flexibility to select a platform that offers strengths specific to the tasks or concepts they wish to highlight in their lesson, without sacrificing an overall quality of student learning.

When asked to list all the details about an object, the word counts of the participant responses were significantly lowest when using the HoloLens. This brevity is perhaps due to the headset slightly impairing users' ability to see the computer screen and keyboard. As the overall complexity of responses did not differ, this suggests that students are still able to achieve expected learning goals despite the condensed nature of their answers.

Assessing Qualitative Learning Results

Each platform offers different means of visualizing digital replicas of artifacts, which in turn directs viewers' attention to different attributes. Overall, SketchFab and HoloLens results were comparable, while 3D prints underperformed in several areas, including the lowest instances of mentions of color and material. As the prints do not have surface details, participants were not able to infer the material of the originals. Mentions of context (time and place) were also the lowest for 3D prints. The lack of visual cues about the material of the object seems to have impaired the overall perception of the "authentic" aspect of the object.

HoloLens responses had a significantly lower mention of facial features over the other two platforms. The reason for this difference is not immediately forthcoming, but may be due to participants' unfamiliarity with the interaction style, which perhaps impaired their ability to zoom in on faces.

Workload Measurement and Enjoyment

Participants' perceived physical demand using the HoloLens was significantly higher. HoloLens use involved standing, moving arms, and in-air gestures that can be physically demanding as well as create accessibility issues. Viewing 3D models on SketchFab and 3D prints can be done while sitting and involve less arm and hand movement. The tactile nature of 3D prints also makes them more accessible to students with visual disabilities [34]. In addition, more than half of participants in the AR condition reported headache or eyestrain while wearing the device.

Of the three conditions, the HoloLens is most novel to participants. Despite the unfamiliarity of the gesture-based interface, we did not find a significantly higher level of frustration while using this AR headset. The HoloLens ranked the highest in enjoyment, followed by SketchFab, and although the 3D prints ranked the lowest they were still perceived as enjoyable overall. The enjoyment ranking results are further supported by the detailed responses about the strengths and weaknesses of each platform. However, longitudinal studies are needed to determine to what extent the novelty of the HoloLens impacted user enjoyment.

Attention Allocation

When asked if the "ancient artifact captured [their] senses," (see Table 4) the participants ranked the 3D prints as trending significantly lower than the HoloLens, although the prints are the only platform to include a sense of touch. Haptic interaction cannot be achieved through traditional museum display, with artifacts behind glass due to preservation concerns. Although the 3D prints offered this novel form of contact with museum objects, participants did not respond as strongly to their perceived level of interaction, as the models were a single color and therefore lacked visual cures such as texture. The importance of haptic interaction for participants with visual impairments should be considered, however, to ensure that educational resources are accessible [25, 53]. Future study design should address the issue of physical model with higher fidelity in terms of color as well as of combining visual information with additional senses.

Spatial Situational Models and Presence

Interestingly, when asked if they still had "a concrete mental image of the ancient artifact," participants ranked the 3D prints the lowest, although they were the only condition that had physically concrete examples in the study. The virtual 3D models allowed the participants to view more physical aspects of the artifacts, such as color and texture, which led to a stronger mental image with lasting impression. The participants confirmed the immersive nature of AR by ranking it the highest when asked if they "felt as though the original ancient artifact was physically present in [their] environment". Once again, although the 3D prints were the only objects to be physically present in the real world, participants ranked them the lowest in this evaluation.

Implications for Design

Each of the three interaction styles employed in this study provides educators with important tools for engaging students. Here, we discuss implications for designers of interactive experiences for object-based learning:

Context

The essential goal of object-based learning is to investigate an artifact in its temporal, physical, and cultural context. The results suggest that participants rely on color and texture to infer the material of the object, and that those visual cues are more important to envisioning context than shapes or volumetric details. As discussed above, the 3D prints had the significantly lowest mentions of color, texture, and material. In order to achieve the learning goals of object-based learning, methods such as computational hydrographic printing [59] or projection mapping [49] could be used to enhance 3D prints. However, such methods still need to become accessible to educators and students through novel and easy-to-use tools.

Perception of size and authenticity

Results regarding the mention of size in participant responses were mixed. This suggests that the three platforms tested in this study do not appear to have inherent qualities that represent a sense of scale. This poses an opportunity for interaction designers to enhance the communication of size and scale through design interventions. Solutions could involve projecting measurements, for example, or providing reference frames and measurement instruments.

Augmented Reality as a classroom tool

The results of this study demonstrate that AR headsets offer a promise for effective use in the classroom. Despite the novelty of the platform and its significant challenges, including the physical effort and the discomfort that ~50% of users experienced, object-based learning goals were achieved in comparable levels to SketchFab. Also, the enjoyment level and reported strengths were highest for the HoloLens despite the discomfort of using the system, though these measures could be impacted by a novelty effect. As educators seek out methods to integrate active learning into their classrooms, the immersive nature of AR headsets uniquely offers a simulated "hands-on" experience while maintaining awareness of activities in the classroom. Although the AR interaction is with virtual artifacts, the physical, kinetic, and gesture-based interactions with virtual objects result in higher perceived presence and sensory interaction than with physical replicas. Interaction designers could further enhance learning by integrating tactile feedback with virtual objects, leveraging emerging technologies (e.g. [5]).

Access and accessibility

Participants achieved object-based learning goals while using freely-accessible content. On-screen direct manipulation is a viable solution in the face of budgetary and logistical constraints, although it was not as enjoyable or physically active as with the HoloLens AR. The potential for 3D prints to make content accessible to people with visual impairment should also be considered. Most importantly, as cultural heritage is captured digitally by researchers, ethical protections for culturally sensitive or endangered material must be taken into account. Increased free access can result in better public understanding of the importance of preserving cultural resources and appreciation for global diversity.

Limitations and Future Work

This study has several limitations that point towards future work. First, we studied one-time use in a between-subjects experiment conducted in laboratory settings. Future work could utilize within-subjects design where participants try more than one interaction style. We also intend to conduct studies of longitudinal use in classroom settings in order to understand to what extent our findings are affected by novelty. Second, our measurement of learning outcomes in this study is limited and does not assess the ability to apply learning to other contexts. We plan to use additional assessment instruments to further measure learning outcomes. Third, the results of this study demonstrate that participants had a strong reliance on visual information for their understanding of artifacts and their contexts. Future studies should incorporate improved methods of 3D printing (e.g. [57]) to test if participants can accept fabricated physical replicas in place of authentic artifacts. Finally, wider application of these technologies in classroom settings should include provisions to be inclusive of different abilities and learning styles.

CONCLUSION

We presented findings from a study, which compares object-based learning outcomes from students as they interact with representations of ancient Egyptian sculptures using three different educational technologies: HoloLens AR headset, 3D model viewing website (SketchFab), and 3D prints. We explored how differences in interaction styles affect the learning process, quantitative and qualitative learning outcomes, and critical analysis. Our findings indicate that both tangible and virtual representations of artifacts can be used to achieve object-based learning goals such as building observation skills, and critically synthesizing information for comparisons. However, differences in interaction styles have significant impacts on various aspects of object-based learning including the learning process, quantitative and qualitative learning outcomes, and critical analysis.

The AR headset, despite its current challenges, which include a high number of participants reporting discomfort, headaches, and physical effort, allowed participants to accomplish object-based learning goals in comparable levels to SketchFab. We believe that most of the discomfort will be resolved in future versions of the AR headset, which could result in even higher learning gains, to be evaluated in future studies. In addition, participants who used the AR system reported higher levels of enjoyment and identified a higher number of strengths for that technology than participants who used the Sketchfab or the 3D prints. The absence of some visual information (color and texture) in the 3D prints hindered students' critical interpretation and contextualization, highlighting a need for making more advanced 3D printing techniques available for educators. While a longitudinal study is needed for further understanding how these technologies facilitate object-based learning, this study demonstrates the feasibility and value of applying interaction with virtual and tangible representations to enhance object-based learning.

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