Making the Invisible Visible in Science Museums Through Augmented Reality Devices

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Abstract

Despite the potential of augmented reality (AR) in enabling students to construct new understanding, little is known about how the processes and interactions with the multimedia lead to increased learning. This study seeks to explore the affordances of an AR tool on learning that is focused on the science concept of magnets and magnetic fields. Seventy students in grades 5 through 7 participated in the study in a non-AR or AR condition. Findings showed that students in the AR condition interacted with the magnets significantly longer and demonstrated higher amounts of teamwork. In interviews, students identified five affordances of the AR on learning that are closely related to the literature on dynamic visualizations, such as the ability to visualize invisible phenomenon and scaffolds that focus attention on relevant information.
Keywords: Augmented Reality; Dynamic Visualizations; Learning

Introduction

In the recent *Horizon Report*, the New Media Consortium discusses the potential of augmented reality (AR) in enabling students to construct new understanding. AR experiences layer digital displays over 3D real world environments (New Media Consortium, 2012) providing access to normally hidden data that individuals can use to develop deeper knowledge about a content area. Previous studies have begun to illustrate AR's potential for learning, particularly in the field of science education (Dunleavy et al., 2009; Squire & Klopfer, 2007). In these studies, the indirect correlates of student learning, i.e., engagement and prior knowledge, are important outcomes of the research and provide valuable impetus for pursuing further studies on what and how students learn. Informal designed settings such as science museums have also begun to explore the use of this technology to create digitally augmented environments. However, research on their impact is largely dominated by usability studies and offers little evidence about how they impact science learning (NRC, 2009).

To address this, over the last few years, our work has focused on how the use of AR devices in a science museum impacts conceptual knowledge and cognitive reasoning skills in children (Yoon et al., 2012a; 2012b). Intentionally designed to impact the public's understanding, attitudes, and behaviors about the natural and physical world around us, science museums are important spaces that support science learning. Indeed, studies have shown that museum visits change how visitors think about and relate to science (Rennie & Williams, 2002), increase visitors' interest, curiosity, and attentiveness to science (Falk & Needham, 2011), improve inquiry skills such as asking questions and offering explanations (Gutwill & Allen, 2010) and understand scientific concepts, models, explanations, and facts (e.g., Falk et al., 1998).

However, assessments that measure scientific knowledge demonstrate little or no positive changes (NRC, 2009). Thus our studies explore how AR can mediate and scaffold visitors' learning of scientific ideas and concepts.

On the topic of electricity, we found significant gains in students' conceptual and cognitive abilities when a device called *Be the Path* (illustrating electrical circuits and conductivity) was digitally augmented to demonstrate the flow of electrons. Observations showed that the digital augmentation helped students engage with the scientific content through manipulating the device to help them confirm or disconfirm their understanding about how to close the path to make a complete circuit (Yoon et al., 2012b). Despite these positive findings, there is still a gap in identifying the mechanisms that promote learning with AR. If we consider such AR technologies under the broader class of educational visualization and multimedia tools, Kuhl et al., (2011) notes that oftentimes, applied research has adopted an outcome-oriented view, where different instructional conditions have been compared with respect to learning outcomes but little is known about how the processes and interactions with the multimedia lead to increased learning. With scant research on AR and learning, fortunately there is a large empirical and theoretical literature base on the benefits of educational visualization from which to build. We refer to this literature in our study to help us explore the potential affordances of an AR tool on learning that is focused on the science concept of magnets and magnetic fields. The specific research question we address is: What are the unique affordances of AR as a visualization tool that impact children's engagement and learning with science devices in a science museum?

Theoretical Considerations

In this section, we review studies that have been done in science museums that reveal affordances of participation with technology. We then discuss other potential affordances based in the literature on dynamic visualizations that may allow us to understand how increased learning occurs.

Affordances of Participation with Technology in Science Museums

Some museum research suggests that technology in interactive exhibits attracts more visitors, engages visitors for longer periods of time (e.g., Borun, 2003), and promotes greater understanding and recall of content than static exhibits (Allen, 2004). In particular, technology-based exhibits have gained attention as having the potential to provide interactive experiences that support learning. For example, Sandifer (2003) found that exhibits that were 'technologically novel', as in they contained visible state-of-the-art devices or illustrated phenomena that would otherwise be difficult for visitors to explore on their own, resulted in significant positive correlations with the amount of time spent by visitors. In other words, visitors spent more time engaged at exhibits that contained novel technology.

Others have discussed the importance of social interaction and collaboration as potential benefits accrued through participation with technology. Laursen (2012) found that children often engaged in various forms of co-participation at technology-based exhibits even though the exhibit was intentionally designed for single user activity. Heath, vom Lehn, and Osborne (2005) found that the design of many of these exhibits, in fact, did not encourage enough verbal exchanges between visitors despite the natural inclination to interact. They suggest that museum designers must place the social and interactional aspects of visitor experiences at the heart of designing technology-based exhibits in order to create a more effective learning environment (Heath et al., 2005).

Affordances of Participation with Augmented Reality in Science Museums

Augmented reality, which is a hybrid between normal reality and virtual reality, has the potential to allow users to experience and perceive virtual elements as part of their present world, thereby enhancing perception and interaction with the real world (Kirkley & Kirkley, 2004). In this way, AR serves as an educational support that provides the user with additional (virtual) information to aid in his/her performance of specific tasks. In museum spaces, this technology is still in the development stage, and research studying its use is largely concerned with design, evaluation, and usability (NRC, 2009). However, these studies have revealed promising findings. For example, Asai and colleagues (2010) reported increased collaborative interactions between parents and their children while participating in an AR lunar surface navigation system. Szymanski and colleagues (2008) found that visitors increased their exploration of objects that were augmented, and Hall and Bannon (2006) demonstrated that children's engagement and interest increased when they interacted with digitally augmented museum artifacts. Although these studies demonstrate that AR has the potential to support learning, more empirical research is needed that determines exactly what and how learning occurs in the presence of these tools.

Affordances of Dynamic Visualizations

To focus on what and how learning occurs in the presence of AR, we align our research with the work on dynamic visualizations, which supports the results of existing science museum studies but also provides additional lenses for which to interpret learning processes. Dynamic visualizations, such as animations and simulations, depict changes continuously over time and represent a continuous flow of motion; this is in contrast to static visualizations that only depict instantaneous snapshots of the phenomenon or process (Schnotz & Lowe, 2008). Because dynamic visualizations can display changes in space over time, they are considered to be more authentic and informative with the assumption that they can improve learners' understanding of the ontological nature of the represented phenomenon (Lowe, 2004; Schnotz & Lowe, 2008).

Dynamic visualizations, due to their unique affordances, can promote deep and meaningful learning. They can help the learner to "visualize" objects and phenomena in the world that are not visible, such as changes in air pressure and temperature on a weather map (Hegarty, 2004; Lowe, 2004). They can visualize entities that are spatially and temporally distributed (Ainsworth & Van Labeke, 2004; Tversky et al., 2002). They can also replace, augment, and focus reality so as to draw attention to relevant parts of the phenomenon (Hegarty, 2004). In this way, they make difficult concepts accessible and allow the learner to consider relations among items that would otherwise be difficult to recognize (Uttal & O'Doherty, 2008). Another advantage of dynamic visualizations is their ability to display abstract information such as evolutionary processes (Ainsworth & Van Labeke, 2004; Rapp & Kurby, 2008; Uttal & O'Doherty, 2008). Thus, dynamic visualizations as instructional tools can improve the real-world experience by providing information that is normally inaccessible in the real world (Vavra et al., 2011). Finally, interactivity is one of the biggest affordances of dynamic visualizations. Interactivity provides learners control over their learning ranging from simple tasks such as playing, stopping, rewinding and replaying a sequence of visualizations, to more complex learning tasks such as changing the parameters and/or data sets of a visualization and constructing their own elements within the visualization (Lowe & Plotzner, 2004). Interactivity, then allows instruction to be uniquely tailored to the learners' needs (Schwann & Riempp, 2004). In adding to this literature base, we hypothesize that as a category of dynamic visualizations, we will reveal affordances of the AR tool similar to this aforementioned research.

Figure 1. Depicts the manipulation of real bar magnets. The interaction is captured by a camera above, digitized and simultaneously fed back in real time with augmented reality magnetic force field lines appearing around the magnets on the computer screen. As the magnets move, the magnetic field lines also move showing different patterns that emerge.

Methods

This study draws on a larger NSF-funded project for which the goal is to understand how museum devices, enhanced by digital augmentations, impact student learning. As seen in Figure 1, the device *Magnetic Maps* allows users to manipulate bar magnets in real time, capturing and displaying the digitally augmented magnetic field depicted by field lines on a computer screen.

Participants and Context

The population of study participants was comprised of 70 students in grades 5 through 7 Students were recruited from a summer day camp at the museum where the study took place and from a suburban charter school. Between the two conditions, 41 percent of the participants were female and 59 percent were male. In terms of grade levels, 59 percent were in 5th grade, 64 percent were in 6th grade, and 7 percent were in 7th grade. According to the local school district curriculum, students are introduced to the concept of magnetism in 4th grade. Therefore we chose this grade band because we wanted to ensure that students already had some prior knowledge of the science content before interacting with the device. Because this project started in the summer, we recruited children who had completed the 4th grade, or were entering 5th grade.

They were randomly placed in groups of three and assigned to one of two conditions. In the first condition (C1), students were presented with the bar magnets as seen in the bottom half of Figure 1 and were instructed to move the magnets and feel what happens. Students in the second condition (C2) were provided the same information as C1 students but were also presented with digitally augmented images of the magnets and the magnetic field on the computer. There were 36 and 34 students in the two respective conditions. Although they were not instructed to work with their group, they were also not discouraged from doing so.

Data Sources and Analyses

Time on task: As a measure of interactivity and engagement, the total time students interacted with the device was recorded. The mean time on task was calculated for each condition and a one-way ANOVA was conducted to see if there was a significant difference between the conditions.

Observations: To understand how students interacted with the device in terms of cognitive behaviors, we used a modified Critical Thinking Skills Checklist (CTSC) described in Luke et al. (2007). Although the CTSC was originally developed to document students' critical thinking in an art museum program, we modified the form to appropriately reflect our study in a science museum. The table below lists the six components we used to analyze student interaction.

Two researchers observed each group as they interacted with the device and checked off behaviors as they were demonstrated or not demonstrated in the activity. After each observation, they came to agreement on what they observed for each student. Mean aggregate scores were calculated for the conditions, and a one-way ANOVA was conducted to see if there was a significant difference between the conditions in each category.

Interviews: To understand the affordances of the AR on learning, we conducted interviews with all 34 students in condition 2 to probe what about the augmentation helped them learn. Four questions were posed: *1)* What did the digital augmentations help you to see? 2) What did it help you to learn? 3) Do you think you would have learned this with or without the augmentations? and 4) Is this different than how you normally learn? Interview transcripts were qualitatively mined by two researchers for themes that illustrated learning affordances as reviewed in the dynamic visualizations literature.

Results

Overall, the analyses yielded encouraging results in identifying learning affordances of the AR tool. In terms of time on task, students in C2 spent more time interacting with the device. The raw scores for mean interaction time with the device were C1= 133.28 seconds and C2= 206.74 seconds. A one-way ANOVA showed a significant difference between the means of C1 and C2, $F(1, 69)=62.87$, $p<.001$.

Results of cognitive behaviors displayed can be found in Figure 2.

Out of a possible score of 6, the mean aggregate score between conditions was C1=2.23 and C2=2.62, which shows that C2 students demonstrated a greater number of cognitive behaviors. A one-way ANOVA revealed a significant difference only in the category of team work $F(1, 69)=4.13$ $p<.05$. Thus the augmentation appeared to have influenced

Observation Checklist Components

	Definition
Participation	Participant physically interacts with the device by operating or manipulating the device.
Interpreting	Participant asks questions and/or explores how the phenomenon occurs.
Team Work	Participant physically and/or verbally collaborates with others during the experience with the device.
Problem-Finding	Participant investigates different configurations to operate the device or reasons for why the device operates a specific way.
Associating	Participants make connections to other science content knowledge.
Comparing	Participant expresses similarities or differences between this experience and other situations or experiences.

Table 1. Note: This checklist is modified from Luke et al. (2007).

students to work together to understand the scientific phenomenon as instantiated in the device. The increased but non significant frequencies of C2 over C1 behaviors found in the categories of *Problem Finding*, *Associating*, and *Comparing* also demonstrates encouraging results that may lead to improved cognition. A larger sample size would likely provide the empirical evidence needed to see a significant difference.

Five categories emerged from the analysis of the interview responses. Table 2 summarizes the categories, examples of each category, and the number of student interviews in which the categories were articulated.

From the table, the affordances that yielded the highest responses were in the categories of *Visible* and *Dynamic*. We were also encouraged to see that just under half of the students believed that the AR technology helped them to see more *details* of the magnetic field phenomenon. Also about a third and a quarter of students respectively said that being able to *interact* with the device as well as the AR *scaffolds* to focus attention were helpful in their learning.

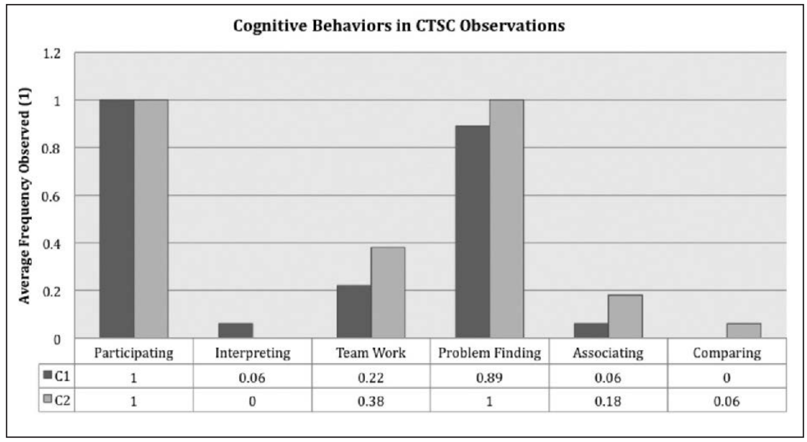

Figure 2. Comparison between C1 and C2 demonstrated cognitive behaviors in the Critical Thinking Skills Checklist.

Discussion and Conclusions

In this exploratory study, we were interested in investigating the processes and interactions with the AR device that could potentially increase learning. Given the shortage of empirical data that reveals the specific learning mechanisms, we reviewed studies on the affordances of dynamic visualizations and hypothesized that learning with the AR tool could produce similar findings about how participants learn. Results indeed showed great overlaps. As *Magnetic Maps* is an interactive device, a larger amount of time spent by students in C2 indicates that students in that condition were physically interacting and engaging with the device more. The interactive quality of the digitally augmented device enabled students to see how the magnetic fields responded to their various actions, thereby allowing the device to be adapted to their needs and interests (Lowe & Plotzner, 2004; Schwann & Riempp, 2004). In anecdotal accounts by the two researcher observers, it was evident that several students tried to make different digital images and patterns appear on the screen by manipulating the magnets in different ways. In one student's interview, he stated, "there were no shapes but you could create shapes, the way the lines moved. We…made a monkey face". When asked what the magnets were doing when they made the monkey face, the student responded, "They were attracting". This response clearly indicates that the interactive feature enabled

Affordance Categories	Description	Example	Frequency of Interview Responses
Visible	Allows users to see things that are normally invisible	*…like I've never seen those before. It's really cool to see the lines…*	25 (73.5%)
Dynamic	Displays the phenomenon in motion showing changes over time	*…the colors and shapes changing.*	19 (55.9%)
Details	Provides scientific details of the phenomenon	*…distance that magnets have before they repel each other.*	16 (47.1%)
Interactive	Enables the user to interact with the device	*…we actually got to touch the things and see it on the screen while we did it.*	11 (32.3%)
Scaffolding	Provides structures that focuses the users attention on relevant information	*…cause the arrows are helping me. It's telling me how it goes.*	8 (23.5%)

Table 2. Categories and Frequencies Found in the Affordances of AR Interview Responses

this group to not only engage with the device creatively, but also to connect their creative play with science content. One of the greatest benefits of interactivity is the ability to shape, arrange, and optimize information with regard to the mental ability of the learner (Schwan & Riempp, 2004). We tentatively suggest that the interactive nature of AR supports science learning.

Another important finding from our study was the ability to visualize specific and dynamic aspects of the interaction between the magnets. Whereas C1 students were able to simply feel the repulsion and attraction between the magnets and thus, only make inferences in regards to the magnetic field, C2 students were able to see not only the magnetic field, but also specific details of the field (i.e., the distance between the field lines) and how the magnetic field changed in response to how they moved the magnets. These affordances align well with previous research findings of dynamic visualization tools. One of the purposes of visualizations (static and dynamic alike) in science is to help imagine the unseen (Phillips et al., 2010). By representing phenomena visually, visualizations can reveal underspecified aspects of the phenomena (Linn, 2003) and the underlying complexities of scientific processes, thereby fostering more comprehension.

Also, the dynamic features of visualizations afford more efficient and explicit communication of information (Kuhl et al., 2011). As the interviews revealed, because students were able to see how their actions changed the magnetic field, they were able to associate these changes with specific details and aspects of the magnetic field. In this way, the digital augmentation acted as a scaffold and specifically focused and directed students' attention towards relevant and important information. For instance, many students accurately interpreted the intensity of the field lines with the strength of the attraction or repulsion between the magnets.

A major finding however, that we feel is an advancement in the literature on dynamic visualizations and learning through augmented reality is the affordance of team participation. The observations revealed that in the presence of the digital augmentation, students were more likely to participate and engage with other members of their group. Even though students in neither group were told to work together, the uniqueness of the tool itself compounded with the affordances mentioned above naturally drew students together. Although there is little research that reveals that dynamic visualizations stimulate group work, Kozma (2003) suggests that it is important for visualizations to support collaboration among students as collective engagement in scientific discourse can lead to deeper understanding. Our finding also addresses the suggestion advanced in Heath et al. (2005) regarding the need to construct intentional designs of technology-based museum exhibits to support social and interactional aspects of visitor experiences for more effective learning.

Finally, an additional advantage of AR is its influence at holding visitor attention for longer. Our results indicated that students who engaged with the augmented device spent a significantly greater amount of time engaging and interacting with the device as compared to students who played with the regular device. This is consistent with previous research that identifies technological novelty as a characteristic of exhibits that significantly contributes to visitor attention (Sandifer, 2003). As informal environments, museums allow visitors great freedom and choice in deciding how, when, and to what extent they direct their attention towards. Though not an absolute measure of learning, museum research has found a positive correlation between learning and time on task (e.g., Falk, 1983). Thus, we suggest that the nature of AR, as a newly emerging technological tool, can also support visitors' learning by holding their attention for longer.

Given this promising finding, we intend to pursue further studies with a larger sample of participants to explore more extensively, how collective engagement emerges through AR interactions to support learning. Moreover, these findings reveal that AR, as a novel technology, offers several of the important learning affordances of dynamic visualizations. These learning processes include the ability to interact with and make visible details and changes in phenomena over time that can provide structure to focus the users attention on relevant information.

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