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Using augmented reality and knowledge-building scaffolds to improve learning in a science museum

Susan A. Yoon · Karen Elinich · Joyce Wang · Christopher Steinmeier · Sean Tucker

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Abstract Although learning science in informal non-school environments has shown great promise in terms of increasing interest and engagement, few studies have systematically investigated and produced evidence of improved conceptual knowledge and cognitive skills. Furthermore, little is known about how digital technologies that are increasingly being used in these informal environments can enhance learning. Through a quasi-experimental design, this study compared four conditions for learning science in a science museum using augmented reality and knowledge-building scaffolds known to be successful in formal classrooms. Results indicated that students demonstrated greater cognitive gains when scaffolds were used. Through the use of digital augmentations, the study also provided information about how such technologies impact learning in informal environments.

Keywords Knowledge-building · Augmented reality · Informal learning

Introduction

The issue of declining participation by America's youth in science, technology, engineering, and math (STEM) education and careers has received a great deal of attention over the last

S. A. Yoon (✉) · J. Wang · C. Steinmeier · S. Tucker
Graduate School of Education, University of Pennsylvania, 3700 Walnut Street, Philadelphia, PA 19104, USA
e-mail: yoonsa@gse.upenn.edu

J. Wang
e-mail: joyce.s.wang@gmail.com

C. Steinmeier
e-mail: cst@dolphin.upenn.edu

S. Tucker
e-mail: tuckers@mail.med.upenn.edu

K. Elinich
Franklin Institute Science Museum, 222 North 20th Street, Philadelphia, PA 19103, USA
e-mail: kelinich@fi.edu

few years from industry, government, and education sectors (Business Roundtable 2005; Domestic Policy Council 2006; U.S. Department of Education 2007). Experts predict that the availability of STEM jobs will continue to increase such that, by 2012, the number of positions in science and engineering will have outpaced the number of qualified people to fill them by 26 % and 15 % respectively (NSF 2006). Additional pressures on workforce development exist with the emphasis on 21st century skills (Partnership for 21st Century Skills 2007) by which learning from and using digital technologies both for developing conceptual knowledge and process skills must figure prominently in education. As new scientific and technological developments continue to impact people's lives, there is further interest in providing educational opportunities that will increase general levels of scientific and technological literacy. Given this enormous need, there is increasing recognition that STEM education can no longer have the sole responsibility of formal schooling. The National Research Council (NRC) report on learning science in informal environments examines the potential that non-school settings such as zoos, aquaria, and museums have for engaging large portions of the population in real-world scientific investigation (NRC 2009). Furthermore, the report notes, where No Child Left Behind requirements have limited the amount of in-school science instructional time, informal programs actually serve as essential venues for learning. However, the NRC report and others (e.g., Rennie et al. 2003) also highlight the need for systematic studies of learning designs in order to realize the potential for the field of informal science to contribute to STEM education and career development.

This study investigated three related critical gaps in understanding of informal learning, as outlined in the NRC report. First, while there is ample evidence of increased levels of interest and engagement, evidence for improved conceptual gains is less convincing. This is partially due to the free choice, episodic structure of activities characteristic of informal environments. Second, as more educational technologies are being used to assist in the development of conceptual knowledge, little is known about how digital platforms improve the learning experience in these informal settings. Finally, while designed interactive experiences have been shown to increase important scientific skills such as manipulating and observing, more challenging cognitive skills, such as reflection, making predictions, drawing conclusions, and theorizing, are less frequently demonstrated. This study considered these critical gaps together by investigating the effects of digital platforms in an informal environment on conceptual and cognitive gains, with particular emphasis on theorizing skills in the content area of electricity. Using knowledge-building scaffolds for peer-to-peer discursive interaction and collective advancement (Scardamalia 2002), the study aimed to determine whether and how learning through digital platforms might be enhanced through a knowledge-building design, which had not previously been applied in informal environments. The research was conducted at a premiere science museum in a large urban city in northeast USA using augmented reality visualization technologies. The specific questions investigated were: 1) To what extent do visualizations of scientific phenomena made possible by augmented reality technology assist learners in developing conceptual understanding in a science museum environment?; 2) How do knowledge-building scaffolds in concert with visualizations improve cognitive abilities?; and 3) Which scaffolds are more or less successful to promote learning in a museum setting?

Theoretical considerations

Three key areas of research in STEM education and the learning sciences informed this study: the use of digital augmentations to support learning, learning in informal environments, and knowledge building.

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Digital augmentations and applications in museums

Augmented reality applications or digital augmentations of real-world phenomena have increased in formal education and other knowledge domains such as medicine over the last few years (John and Lim 2007; Klopfer and Squire 2008). While there is a lack of consensus on a definition for augmented reality (AR), we follow Azuma's (1997; Azuma et al. 2001) characterization of the properties of AR environments, which include real and virtual objects in the real environment, alignment of real and virtual objects with each other, and their interaction in real time. In this study, we refer to the users' physical experience with the augmented device as "augmented reality." We differentiate this from "digital augmentation," which we define as the computer-generated image that is superimposed upon the physical environment. Thus, we specifically study the effects of this digital augmentation on museum visitors' levels of understanding.

Within the museum research literature, there has been some emerging focus on how digital devices improve engagement to enhance the visitor's experience. For example, Szymanski et al. (2008) tested a prototype handheld device that delivered descriptions of artifacts in a historic house to multiple users simultaneously, and found that conversations around exhibits increased. Waite et al. (2004) found that their technology, MUSEpad, offered opportunities for visitors with vision, hearing, and mobility impairments to experience increased engagement with museum exhibits through, for example, marking the location of elevators on maps and adding closed captioning. In another study, increased engagement and interest was also found with young students when they were given RFID sensors that could detect exhibit locations and unlock virtual information to extend their interactions (Hall and Bannon 2006). Hughes et al. (2004) report a case study through which they augmented a traditional museum dinosaur exhibit with a mixed-reality encounter with ancient sea life. Their intent was to enrich experiential learning for children at the museum.

Along similar engagement lines, other studies have examined how AR can improve access to information and increase exhibit functionality. For example, Damala et al. (2008) investigated the functionality of an AR-enabled mobile multimedia museum guide implemented in a fine arts museum in France. They found, among other things, that using AR to enhance the museum experience could serve as a viable alternative to traditional text guides in retrieving information, which has potential to attract new audiences. Over the last few years, Sylaiou et al. (2008, 2010) have developed and evaluated the Augmented Representation of Cultural Objects (ARCO) system which provides museum curators with digital tools to construct web and AR-enhanced educational kiosks on the museum floor. The stated purpose of the system is to offer an entertaining and enjoyable experience to museum visitors. While AR studies in museums are continually emerging, it is evident that much of the research centers on how to increase engagement, interest, and usability rather than on what visitors learn and how learning can be improved. This situation is, in part, due to the unique constraints and affordances of learning in informal learning environments, which we briefly review in the next section.

Learning in informal environments

As noted in the NRC (2009) report and elsewhere (Squire and Patterson 2009; Honey and Hilton 2011), learning in informal spaces is fluid, sporadic, social, and participant driven—characteristics that contrast with the highly structured formal classroom experience. As such, it is important to understand the various types of learning that commonly occur in these free-choice environments. For example, many researchers focus on changes in individuals' affect, such as increased excitement, interest, and motivation in science, as important learning outcomes (Allen 2002; NRC 2009; Perry and Tisdal 2004). Others have focused on the development of a scientifically literate public who are capable participants in the culture of science (Borun et al. 2011). These studies highlight the *potential* that informal environments have not only in educating the public to make informed decisions on socio-scientific issues but also in changing the public's relationship to science (Borun et al. 2011; Dierking et al. 2004; Falk et al. 2007; Rennie and Williams 2002), including changes in individuals' conceptual understandings of scientific ideas and processes of science.

Some studies have identified the positive effects that informal environments have in improving visitors' knowledge of specific scientific concepts and facts (Eberbach and Crowley 2009; Marek et al. 2002), but the findings to date are limited. This is, to some extent, due to how learning events are structured; activities are often experienced in single-visit episodes (Falk et al. 2007) where visitors learn on their own with little follow-up or reflection. To promote greater refection, there is some evidence from museum visitor studies, that greater cognitive gains can be achieved when objects are accompanied by learning scaffolds such as social interaction (Fender and Crowley 2007; Palmquist and Crowley 2007; Sanford et al. 2007) and interpretive labels (Allen 2002; Serrell and Adams 1998).

Despite the potential for learning, evidence has been limited, in part, due to the challenges of doing sustained learning research in informal settings such as museums. McManus (1994) has characterized typical visitors as demonstrating scouting behaviors within museum exhibits, where they roam around, encounter devices, and act quickly to discover the intended information. Thus, more systematic learning studies are difficult to design. However, if we are interested in developing programs in science museums that impact learning, we need to capture experiences of a more attentive participant. Fortunately, another kind of population that museums serve, that is different from the typical informal visitor but no less important, is the school group. School groups are often more focused in their explorations and participate in designed activities (Stavrova and Urhahne 2010). Science and technology education researchers have increasingly worked with school groups to understand how to better design experiences to increase the likelihood that successful learning outcomes occur (DeWitt and Osborne 2010; Stavrova and Urhahne 2010).

Our study attempts to extend this line of inquiry to help understand how improved conceptual knowledge and theorizing skills can be achieved within a museum setting, particularly in small social school groups. A consequence of selecting school groups as our research population is that we position our work at one end of the informal learning spectrum. By sacrificing some of the fluidity and unpredictability of informal learning, we can focus attention on the AR technology itself and its characteristics in order to offer evidence of how it can be used as a learning tool. Ultimately, we anticipate that the evidence will suggest strategies for influencing learning in even the most purely informal experience. In addition to the visual scaffolding provided by the AR application, we were interested in investigating the impacts of pedagogical scaffolds that are specifically geared toward increasing learning. For this we turned to a canonical research program in the learning sciences–knowledge building, which is briefly reviewed below.

Knowledge building pedagogy and scaffolds

For almost 30 years, examining how students build knowledge through computer supported intentional learning environments has been the focus of knowledge building research (Bereiter 2002; Scardamalia 2002; Scardamalia and Bereiter 2006). Knowledge-building pedagogy is premised on the belief that students can participate in authentic knowledge work, much like experts do, through peer-to-peer exchanges and collective improvement of ideas. Bereiter and Scardamalia (2003) suggest that most formal educational experiences are designed for students to participate in *belief mode* where ideas are investigated and proved or disproved with evidence for or against. They argue instead for learning to take place in *design mode*, which is concerned with the "improvability and developmental potential of ideas" (p. 56) similar to the way that knowledge work is done in the real world. Several central goals of this approach include: knowledge advancement as a community, idea improvement, using discourse for collaborative problem solving, and constructive use of authoritative information (Scardamalia and Bereiter 2006). Because knowledge building requires the development of a community with shared understanding, language, and goals, learning events evolve over longer periods of time than informal environments may afford. Van Aalst (2009) characterizes learning experiences that are less focused on the community as knowledge construction in which students may collaborate in small groups on tasks that require less synthesis and reflection on the knowledge advancement process. We recognize the limitation of our environment and population in terms of achieving a true knowledge-building community, however, we are interested in understanding how aspects of knowledge-building pedagogy can be applied in informal environments given its success in formal classrooms. We describe the specific pedagogical elements and their theoretical underpinnings that we have adapted below.

The technological application, Knowledge Forum and associated pedagogy use educational scaffolds to enable public, collective contributions that shape the knowledge constructed in the learning community. Because museum visits are episodic and do not allow for the extended time on task that is a prerequisite for the effective development of a knowledge-building community, it is essential to adapt existing knowledge-building scaffolds to function within the constraints of a single museum visit. Scaffolds, in the form of *prompts,* were designed to promote idea advancements, generalizations, differentiation between evidence and theories, and peer sharing. For example, a prompt such as "*My theory is…*" encourages students to use evidence to construct a more general understanding of a class of scientific phenomena. Similarly, students can create a "rise above" note, enabled by the *archived database* of peer exchanges, which is a distillation of an idea or theory from a collection of previous peer exchanges that provide students with opportunities to think across diverse perspectives and to arrive at conclusions about how the collective learning community views a scientific issue (Yoon 2008).

Collaboration also factors prominently into the knowledge-building approach. By working with others discursively to problem solve, evaluate evidence, and identify important *shared understanding*, students are able to more deeply reflect on what they know rather than learning independently, or learning through textual modes (e.g., interpretive labels). This decentralized, public, and distributed participation promotes what Scardamalia (2002) calls *collective cognitive responsibility* where the impetus for learning is *generated by commitments to improve ideas* within the community rather than by teacher directive. We hypothesized that using a knowledge-building pedagogy would work well in a museum environment due to the fact that visitor experiences are normally participant-driven and could potentially benefit from supports that encourage social interaction. Given the sporadic nature of most museum visits, we could not directly transfer knowledge-building scaffolds onto the museum floor. Thus, from this set of theoretical and pedagogical descriptions, the study uses adaptations, which we collectively refer to as knowledge-building scaffolds, including: knowledge prompts, a bank of peer ideas, working in collaborative groups, instructions for generating consensus, and student response forms for recording shared understanding. We hypothesized that these scaffolds would promote collaboration within the peer groups by encouraging students to discuss their observations and reflections of their experience.

Methodology

Participants and context

In an attempt to mitigate the research complexities associated with informal science learning, the study focused on students who visit the museum as part of a school field trip. They represent a key segment of the informal science learning population. Every science museum depends significantly on them and devotes extensive energy and resources to serving their needs. While on their field trip, students encounter science exhibits in small chaperone-based groups of, typically, six to nine children. For this study, we used the chaperone-based small group model as our participant paradigm.

Students from grades six, seven, and eight participated in the study. We recruited teachers to bring their students who had previously participated in workshops and other teacher events at the museum or were referred to us to participate in the study by those teachers. All of the participating student groups came from a high needs urban school district with an average of 92 % of students qualifying for free or reduced price lunch. In total, 119 students participated, with a gender ratio of 55 % female to 45 % male.

Because the study addressed the topic of electrical conductivity, middle grade students were selected as they would have encountered this topic in their classrooms by grade 6 (as dictated by the local standardized curriculum). This provided a common ground for the participants, ensuring similar prior knowledge.

Once a teacher accepted the invitation to participate in the study, the informed consent process began. We provided parent letters and consent forms which the teacher distributed to students and collected for us. A mutually convenient date for the field trip was identified. On the day before the trip, we went to the school and administered a conceptual knowledge survey, described below. The teacher had no access to the survey questions so as to control for potential interference. On the day of the field trip, the students traveled with their teacher and chaperones by bus to the museum and were greeted for orientation. As is the norm for school field trips, the students had approximately 4 h to spend at the museum before they needed to be back on their buses for the return to school. Approximately 25–30 min of that time was spent participating in this research study. The rest of the time was free for them to explore the museum. As mentioned above, the typical chaperoned field trip model applied, with each chaperone instructed to bring a sub-group to the research area at a specified time. Upon arrival and orientation, one group proceeded immediately to participate in the study while everyone else went to explore the exhibits, knowing when they should return to the research area. While in the research area, each student interacted with the device as part of a group of three, but otherwise had no exposure to what other students in the class were doing.

Technology

The study was made possible by a current National Science Foundation (NSF) informal science education project in which the central goal is to design, integrate, and investigate the use of educational technologies within an informal science learning experience. Several tools are under construction including digitally augmented exhibit devices. While the larger project focuses on the viability of using augmented reality technologies in science exhibits, the present study extended this focus by investigating how scientific concepts may be learned through such applications, especially the addition of a digital augmentation. This investigation used an exhibit device called “Be the Path” that illustrated electrical conductivity and circuits. The device existed in both its traditional hands-on state as well as a novel augmented condition. In its traditional state, it featured two metal spheres on a table, approximately one foot apart, with one connected by a wire to a battery and the other connected to a light bulb. When the user grasped the metal spheres, the circuit was completed and the bulb on the table glowed. The posted label on the device provided minimal direction, simply suggesting, for example, that the user "try to complete the circuit." The intent was for visitors to recognize that the human body could conduct the flow of electricity, essentially allowing them to "be the path." In order to extend and enrich the interactive experience, the exhibit developers created a novel augmented variation of the device (see Fig. 1). Using fixed position equipment, the device was enhanced with a camera, digital video projection system, and computer running EyesWeb software. The augmented reality technique known as background differencing was used to recognize the visitor's position around the device. When the circuit was completed, the lit bulb triggered the projection of an animated flow of electricity on the visitor's hands, arms, and shoulders—showing the complete loop and visualizing the flow of electricity through the completed circuit. If the visitor released their hold on the spheres, the circuit was broken and the visualization instantly disappeared. When the circuit was closed it reappeared. This application of augmented reality technology was deliberately "gear free" with no special equipment needed for the visitor to interact with the digital augmentations—a fundamental research premise of the larger NSF project.

Research design

The participating students were grouped into four conditions. The conditions were designed to represent increasing use of scaffolds for learning through digital augmentations and knowledge-building scaffolds. All four conditions involved a simple student response form, described in detail below, which would be used to collect student data. Condition 1 (C1) served as the control group with no digital augmentations or knowledge-building scaffolds. These students interacted with the traditional, non-augmented version of the device. Condition 2 (C2) represented the device with the digital augmentation but no other scaffolding. This condition was designed to represent the average museum visit experience with participation mainly through hands-on sensory experiences or trial and error (NRC 2009). Conditions 1 and 2 also directly address the first research question, which is to understand the impact of digital augmentation on conceptual understanding. Condition 3 (C3) featured light scaffolding in which labels in the form of directed questions were posted at the device for participants to reference while interacting with it and its digital augmentation. This condition was designed to represent the common scenario in which exhibit designers provide labels, signs, and explanations with the expectation that visitors will read them. The posted questions were: What happens when you touched both metal spheres? When you touched

Fig. 1 "Be the Path" device with digital augmentation

only one? What happened to make the bulb light up? What does the projection show? What are you supposed to learn by using this device?

Condition 4 (C4) represented the condition in which both digital augmentation and knowledge-building scaffolds were used. Students were instructed to work in groups of three. Each group was given the same posted questions as students in Condition 3 and additionally directed to brainstorm possible answers, give reasons for each, decide as a group, and write their collective response on a shared response form while they were interacting with the device. These directions were printed on the form, but read aloud by the researcher in order to make sure that they were known. Other knowledge-building scaffolds were added to the student response form in the form of directed prompts such as "*Our hypothesis is…*" and "*Our theory is…*" Students also had access to a posted bank of answers that other students had previously provided. The intent was for students to use the bank in order to evaluate their own ideas against others through two more knowledge-building scaffolds: "*Others have said…*" and "*We agree/disagree with them because…*" Conditions 3 and 4 were constructed to respond directly to the second two research questions, which investigated whether knowledge-building scaffolds increased cognitive skills and which scaffolds were most useful in informal environments.

Students were randomly assigned to the four conditions. As the study was embedded in a whole class field trip to the museum, we wanted all students to participate in the activity. However, logistical factors (e.g., absence during the pre- or post-intervention survey administration) caused variation in the number of participants we were able to analyze for each condition as an incomplete data profile existed for some individuals. We acknowledge that the variability in numbers per condition presents some challenges in interpreting the findings, which we discuss later. See Table 1 for the number of participants in each condition for whom we were able to conduct complete data analyses.

Learning environment—Configuration and orientation

We configured the learning environment (see Fig. 2) to probe the application of varying levels and combinations of scaffolding as described above. We oriented the students to the environment accordingly, explaining each scaffold to the students using a scripted introduction upon their arrival in the testing area. For example, when the condition included posted questions that mirror the response form that they would use for recording their understandings, the researcher first directed their attention to the poster and read the questions aloud to the students before they were allowed to begin. When the group work scaffold was added, instructions for how to work together were posted on the wall and read aloud to the students. When the bank of peer ideas was present, the students were urged to consult it before they began interacting with the device. In all cases, the researchers followed a script to orient the students to the environment and

Table 1 Number of participants in each condition

Condition	Number of students
1	18
2	22
3	31
4	16 groups of 3 (48)
Total students	119

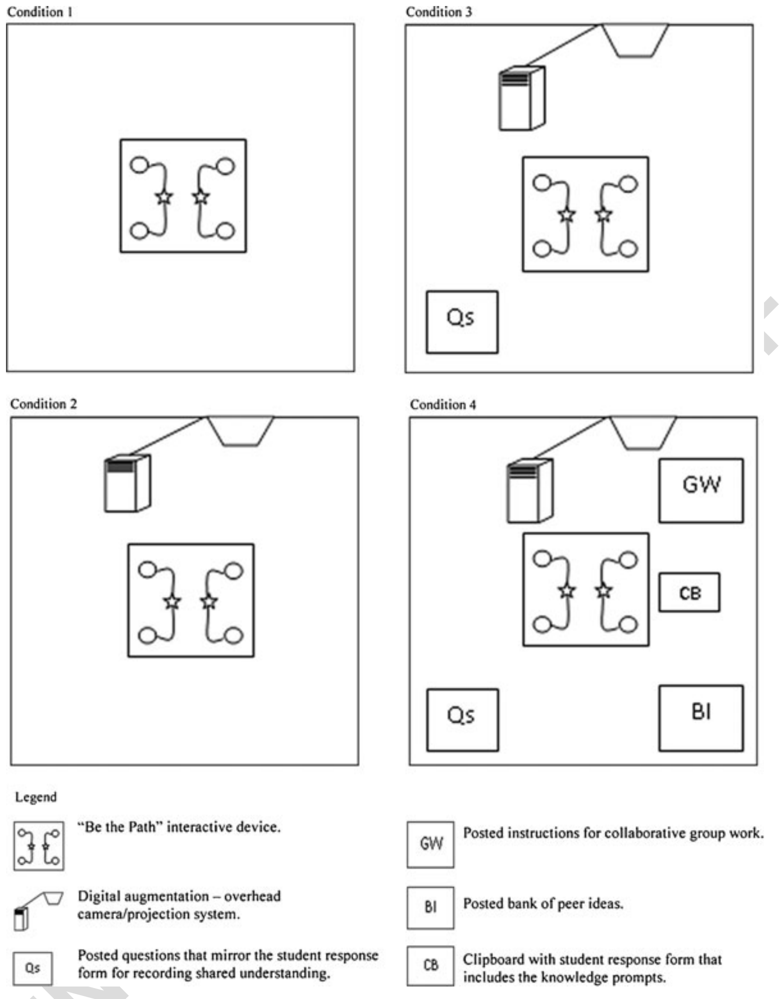


Fig. 2 Configuration of the learning environment

to provide common, consistent guidelines for how to make use of the scaffolds that were present for their condition.

Data sources and analyses

Five data sources were collected and analyzed through a quasi-experimental mixed-methods approach: surveys, student response forms, interview responses, observation notes, and video footage of student interaction with the device. Each data source is detailed below.

Surveys A conceptual knowledge survey was administered to students in each group before and after the intervention. The survey posed five general multiple-choice content questions each valued at one point, related to the scientific topic of electrical conductivity and circuits. The five questions were:

1) Lightning is a discharge of (____).
2) Which class of elements best conducts electricity?
3) (____) is an example of a good conductor.
4) (____) is an example of a good insulator.
5) Which of these is the best definition of an insulator?

An additional open-ended question on the survey also solicited responses that demonstrated knowledge directly related to the device experience, i.e., "Think about an electric circuit that supplies electricity to a light bulb. What parts make it work so that the bulb lights up?" Responses to this question were coded on a five-point Likert scale from no understanding (0) to complete understanding (4). Refer to Table 2 for a description of the levels of understanding and the coding rubric. In total, the highest possible score on the conceptual knowledge survey was nine points—five points from the multiple choice section plus four points from the open-ended question. A paired-samples *T*-Test was conducted to determine whether there was a statistically significant gain in conceptual knowledge within each condition. A repeated measures ANOVA was conducted on the data set to determine whether there was a statistically significant difference between the mean gains. For this survey, we weren't able to conduct a multilevel analysis due to the small sample size but we are aware of the limitations of the non-independence issues that can potentially impact results, particularly for students in Condition 4 who worked in groups. Cress (2008) discusses two important non-independence factors that pertain to our study; *common fate*, which is the tendency to become similar over time due to only being exposed to the same group; and *reciprocal influence*, which has to do with group members being strongly influenced by other group members. As Cress (2008) also notes, computer-supported collaborative learning environments are designed to be influenced by group interactions and we intentionally designed the conditions to understand how working in groups as a knowledge-building scaffold can impact understanding (see Fig. 5).

Student response forms A student response form was used to gather data from all participating students, regardless of condition. Students in Conditions 1, 2, and 3 completed the form individually immediately after they finished interacting with the device. They moved away from the device to be seated at tables for the task. Students in Condition 4 actually completed the form during the group experience with a single form on a clipboard being used for their collective response. Each group of three was allowed to negotiate the work process for themselves. For example, some groups elected a single scribe while others passed the clipboard around to share the scribe duties. The following four to five descriptive questions were asked:

1) What happened when you touched both metal spheres?
2) What happened when you only touched one metal sphere?
3) What happened to make the bulb light up?
4) What does the projection show? (Condition 2–4 only)
5) What are you supposed to learn by using this device?

The last question was intended to elicit responses that demonstrated students' ability to theorize from the interaction with the device, i.e., understanding of electrical circuits and how the human body functioned as a conductor. Responses were coded on four levels from no understanding (0) to complete understanding (3). Refer to Table 3 for a description of the levels of understanding and the coding rubric. A perfect score for the response form, therefore, would be three points. An ANOVA was conducted on the response data set to determine whether there was a statistically significant difference in responses between the conditions and a post-hoc Tukey HSD comparison was conducted to determine the source of the difference.

Q1

t2.1 **Table 2** Levels of understanding on conceptual knowledge survey

	Levels of understanding	Description
t2.2	Levels of understanding	Description
t2.3	Level 4 – Complete understanding (+4 points)	• Student identifies all the major components of a complete circuit including the power source, the method of transfer, and the output.
t2.4		• Student identifies the power source as a battery. (Potentially could be a power plant, but would have to demonstrate a loop or complete circuit.)
t2.5		• Student identifies a complete loop or circuit composed of a conductive material such as wires, cords, or human body.
t2.6		• Student indicates an accurate flow of current from the battery to the bulb.
t2.7		• Student identifies the output as the bulb lighting up or demonstrates that electricity has achieved its intended use.
t2.8	Level 3 – Partial understanding (+3 points)	• Student identifies all the major components of a complete circuit including the power source, the method of transfer, and the output.
t2.9		• Student identifies a power source as a battery, power plant, or an outlet/socket.
t2.10		• Student identifies a circuit (thought it may not be a complete or closed loop) composed of a conductive material such as wires, cords, or human body.
t2.11		• Student identifies the output as the bulb lighting up or demonstrates that electricity has achieved its intended use.
t2.12	Level 2 – Emergent understanding (+2 points)	• Student identifies that there are multiple components of a circuit and that there is a process or system in place to make the bulb light up. Something is transferred from a power source to make the bulb light up. Answers may neglect components of a complete circuit and may contain misconceptions.
t2.13	Level 1 – Little understanding (+1 point)	• Student identifies that something works to make the bulb light up. The power source may include a "magic" switch in which the student recognizes that a switch turns on the bulb but does not have an understanding of a circuit. There may be too much emphasis on only one specific component that makes the bulb light such as the switch or the wires. Answers are missing major components of a complete circuit and contain major misconceptions.
t2.14	Level 0 – No understanding	• Student does not answer, identifies that they do not know the answer, or does not provide evidence that connects the illustration and the description to the key words.

For both the survey and student response form open-ended questions, we used strategies from Strauss and Corbin (1998) to conduct the qualitative analysis. We constructed a categorization manual through iterative negotiation. In developing the manual, we consulted with experts in physical science and informal education who are on staff at the museum in order to develop a scoring rubric. They helped us determine the scope of an ideal, age-appropriate response to the questions. Once the manual was complete, we used it to code the data systematically.

To obtain external validity, two professional colleagues with educational experience at the museum who were not familiar with the study were trained on the coding protocol.

t3.1 **Table 3** Levels of understanding on student response form

	Levels of understanding	Description
t3.2	Levels of understanding	Description
t3.3	Level 3 – Complete understanding (+3 points)	• Student identifies that the human body can *complete a circuit* AND can *conduct electricity.*
t3.4		• Student identifies both concepts (completed circuit & conductivity).
t3.5		• Student demonstrates accurate understanding of both concepts, even if the terms "circuit" or "conduct" are not explicitly used.
t3.6		• Student correctly uses simile or metaphor to explain concepts.
t3.7		• The answer may not contain any misconceptions.
t3.8	Level 2 – Partial understanding (+2 points)	• Student identifies that the human body can *complete a circuit* OR can *conduct electricity.*
t3.9		• Student identifies either or both of the concepts, either by correctly using the terms or describing how it applies to the experience.
t3.10		• Student demonstrates accurate understanding of either or both concepts, even if the terms "circuit" or "conduct" are not explicitly used.
t3.11		• Student correctly uses simile or metaphor to explain concept.
t3.12		• The answer may contain misconceptions.
t3.13	Level 1 – Little understanding (+1 point)	• Student identifies that something they did caused the bulb to light up but the answer does not refer to either concept (completing a circuit or conductivity) and contains misconceptions.
t3.14	Level 0 – No understanding	• Student does not answer or identifies that they do not know the answer.

Cronbach's alpha on over 20 % of the data for the pre-/post-surveys and the student response forms were 0.936 and 0.948 respectively.

Interviews In order to investigate how knowledge-building scaffolds impacted the nature of the experimental intervention, 10 groups (30 students) in Condition 4 were randomly selected for short group interviews immediately following their interaction with the device. We asked the students to evaluate each of the scaffolds they encountered in order to understand which were more or less impactful on their experience. The student responses for each scaffold were tallied and a chi-squared test was conducted on the frequencies in each scaffold category.

Observation notes and researcher reflections The fourth data set integrated observation field notes and anecdotal reflections from the five researchers. These notes and reflections were used to triangulate findings from the other data sources and also to provide plausible rationales and further hypotheses that might explain the results we obtained.

Video footage of student interaction Finally, videotapes of student interaction with the device were used to investigate the dynamics of collaboration as they were potentially mediated by the digital augmentation. Once the conceptual knowledge surveys and response forms were analyzed, the research team collectively reviewed the video footage to identify essential elements of the collaboration process that emerged in Condition 4 group interactions that possibly explained the results. We present examples of transcribed footage that provide insight into the computer supported collaborative nature of group interactions.

Results

Development of conceptual knowledge in the four conditions

Figure 3 shows the mean raw scores obtained for pre- and post-intervention conceptual knowledge surveys in all four conditions. Over all, across pre- and post-intervention surveys, the means were low, ranging between 2.625 to 3.682. Students in C2 (the condition with just the digital augmentation) had the greatest gains and the highest raw score on the survey. This result confirms our findings that the digital augmentation, in and of itself, is an effective scaffold—a result seen in earlier phases of this research and previously reported elsewhere (Yoon et al. 2011).

Table 4 shows the results of paired-samples T-Tests conducted within each condition. The table shows that gains in all experimental conditions were statistically significant. (Recall that C1 was the control.) However, the repeated measures ANOVA showed no significant differences between the mean gains.

Development of cognitive skills

The analysis of student response forms that evaluated students' abilities to generalize about electrical circuits and conductivity yielded some positive results toward understanding the impact of the different study conditions. Figure 4 shows an increasing trend from C1 to C4 in the means obtained for cognitive theorizing ability. Out of a possible score of 3—which indicated a complete understanding—students in C4 scored the highest with a mean score of 2 (representing the category of Partial Understanding) while students in the remaining conditions scored between 1 (Little Understanding) and 1.5.

An ANOVA showed a significant difference between the means of the four conditions, $F(3, 83)=4.560$, $p=.005$. A post-hoc Tukey analysis showed that the difference was attributable to the higher mean of C4 which was significantly higher than C1 ($p=.004$) and C2 ($p=.028$), and marginally higher than C3 ($p=.077$). Sample responses from students in C4 along with their codes compared to responses from students in other conditions illustrated these results:

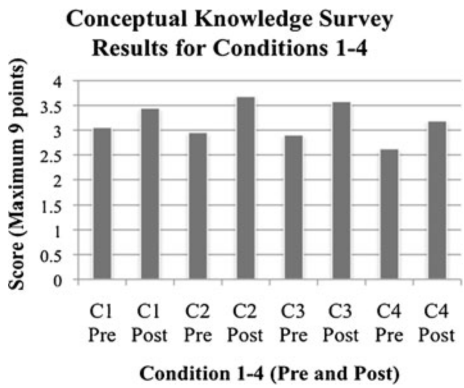


Fig. 3 Graph showing means of the raw scores obtained for pre- and post-intervention conceptual knowledge surveys for Conditions 1–4

Table 4 Results of paired-samples T-Tests comparing means within conditions

Condition	Mean difference	SD	*t*	*df*	Sig. (2-tailed)
1	0.389	1.819	0.907	17	0.377
2	0.727	1.077	3.167	21	0.005*
3	0.677	1.833	2.058	30	0.048*
4	0.562	1.413	2.758	47	0.008*

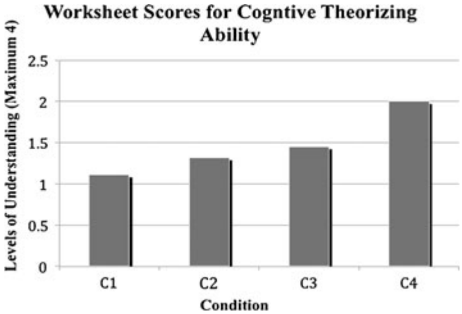
*$p<0.05$

Student 1 (C4) I learn the body can act like wires to connect stuff and there are electric charges in the body. (score=3)
Student 2 (C4) How our body transported electricity through the circuit into the metal spheres to make the bulb and images appear. (score=3)
Student 3 (C2) You have electrical currents in your body. (score=1)
Student 4 (C3) How energy flows through your body. (score=2)

Impact of scaffolds

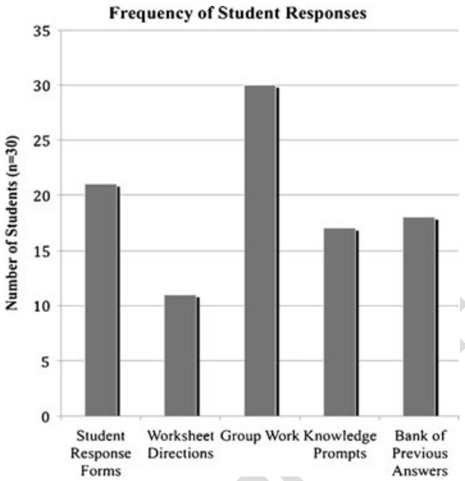
In order to probe the impact of the different kinds of scaffolds, students in Condition 4 were interviewed after their interaction with the device. They had encountered all of the scaffolds including the digital augmentation, the response form, the directions on how to work in a collaborative group listed at the top of the response form, the instructions to work as a group, the knowledge-building prompts, and the bank of answers from other groups. We asked them to evaluate the knowledge-building scaffolds for us. Figure 5 shows a graph of student responses in each of the categories. There was unanimous agreement that collaborating in a small group was helpful while the directions at the top of the form were least often identified as helpful. Greater than 50 % of the students said that the remaining three categories of scaffolds were helpful. When asked what they thought was the most and least helpful scaffold, 100 % of the students identified collaborating in a group as most helpful. The least helpful scaffolds were identified as the knowledge prompts (57 %) and the directions (37 %). However, there is some evidence to suggest that students had difficulties understanding why the prompts were included. For example, one student said, “We didn’t even know what they was about, like, but we just put an answer that others have said, like on the board.” When students did understand the rationale behind including the prompts, their helpfulness increased. For example, one student answered, “Because we knew what we was supposed to give. Like the hypothesis, what we believe it is, and the theory is what we think it is.” Other students said that they weren’t accustomed to answering questions like that. Thus, responses to whether or not students felt the knowledge

Fig. 4 Graph showing mean scores for cognitive theorizing ability for Conditions 1–4



Q1

Fig. 5 Graph showing frequency of Condition 4 student responses when asked whether these categories of student response form and knowledge-building scaffolds were helpful



prompts were helpful appeared to be influenced by their familiarity or understanding of the prompt vocabulary such as "hypothesis" and "theory."

Regarding the printed directions on the shared student response form, some students stated that they didn't read them because they were just focused on answering the questions. The following interviewer and group exchange illustrates this point:

Interviewer: All right, remember these directions in the box. OK? Did these directions help you figure out how to come up with the best answer?
Student #1: Didn't read them.
Interviewer: You didn't read them?
Student #1: Nope.
Student #2: I didn't see it.
Interviewer: What about you?
Student #3: I didn't read nothing.
Interviewer: You didn't read them. Okay. So why did you guys not read this?
Student #1: I don't know, it's just like…
Student #2: 'Cause we was studying. We was focused on the questions.

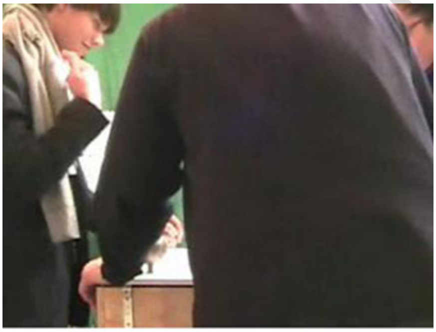
Comments in the researcher field notes and anecdotal reflections also support this finding. Students were rarely observed to be following the group work directions explicitly, although being told to work as a team did at least provide a needed practical scaffold and the students did express a positive opinion of group work. Rather than following the explicit directions, however, they tended to reference existing interpersonal behaviors, which proved to be variously effective in accomplishing the task. Still, considering that students in Condition 4 showed greater ability to generalize from the experience (Fig. 4), the response form and knowledge prompts seemed to provide some utility in terms of learning the content. A chi-squared analysis revealed a statistically significant difference between the frequencies found in the five categories, x^2=9.96, p=.041.

Evidence of computer supported collaborative learning

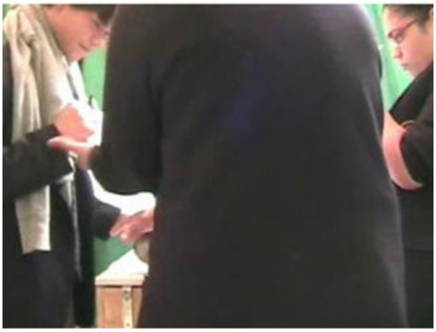
From the video footage of students in Condition 4, we see further qualitative evidence of the influence of the knowledge-building scaffolds and the digital augmentation on learning. The following series of discourse[1] interactions and screen shots illustrates how two groups of students worked together to respond to the student response form questions.

In the first excerpt, three students, B1 (boy with shirt hanging around neck), B2 (boy with back to camera), and G (girl wearing glasses) interact with each other and the digital projection to discover that electricity flows through their bodies.

1. G: ((Reads questions aloud.)) So what happens when you touch only one?
2. B1 and B2: ((Both reach to touch the metal spheres. Projection comes on.))
3. B1: When you only touch one, nothing.
4. B2: Wait wait, what?
5. G: Just touch one.
6. B1 and B2: ((Both reach out to touch the spheres again.))
7. G: Touch this one. ((Gestures to the ball on G's right hand.))
8. B2: ((Reaches over to reposition to B1's hand. Bulb and projection turn on when B2's hand is on top of B1's hand, which completes the circuit with his own hand.)) You gotta touch it yourself.
9. B1: I get it. All right all right. ((Grabs B2's hand.)) Touch that one. ((Gestures B2 to touch one of the spheres. View is blocked by B2's back)). See?
10. B2: Awesome.
11. B1: It's like a circuit. It says right here. It goes around the body. ((Gestures with his hands how the electricity flows around his body.))



12. B1: ((Places both hands back onto the spheres.))
13. B2: All right all right. Give me your hand. Touch it. ((Grabs B1's right hand. B1's left hand is on the left sphere. Places own hand on B1's right sphere, thus completing the circuit and making the bulb light up.))



14. G: Let me use your back. ((Moves to write on B2's back.))

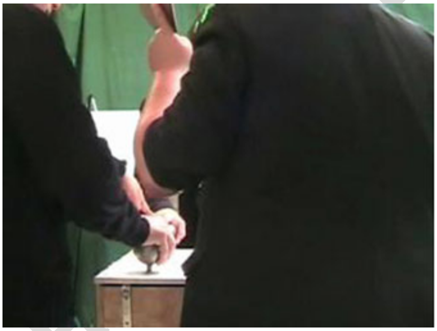
[1] In the written discourse account, gestures and descriptions of on-going dynamics are encased in double parentheses, e.g., (()), direct utterances are written in normal text, instances where utterances are overlapping are encased in square brackets, e.g., [ ], and time elapses are marked in single parenthesis with the number of seconds that have gone by, e.g., (5).

Excerpt 1 (46:45–49:25)

15. B1: Yeah, you get it? ((Smiles)).
16. B2: Awesome. That's cool.

(65)

17. G: Ok, number four. What does the projection show?
18. B2: ((Looking off at a board)).
19. B1: It looks like electricity…like electricity. ((Has both hands on the two metal spheres connected together.))
20. B2: ((Places one hand on top of B1's hand on the right sphere.))
21. B1: Oh, like the thing you see on TV. ((Removes right hand from sphere)).
22. B2: Like it's circulating. ((Reaches over with left hand and places it on top of B1's left hand, which is on the left sphere. Laughs.)) No, it's not static. ((Removes left hand.)) It's circulating.
23. G: ((Places hand on top of B2's hand, which is on right sphere.))
24. B1: ((Refers to G's hand.)) [You can't, cause you're not touching it.]
25. B2: [It's circulating. It's basically circulating on the-]
26. B1: [All right, wait. Ok. Wait. So go.] ((Moves to an adjacent position and places hands on two spheres that are not connected together.))
27. B2: ((Touches B1's right hand with his index finger.))



28. G: Oh, ok.
29. B1: Come here. Come here. ((Inaudible.))
30. G: ((Reads aloud their response being written down.)) It shows us that if you. What's this called right here?
31. B2: Sphere.
32. B1: A ball.
33. B2: It circulates around us. It circulates.

As the group engages with the device (lines 1–10) the questions prompt them to attempt other configurations to make the bulb light up. In line 11, B1 makes the connection that the electricity is flowing in and around their bodies like a circuit. B2 then tries another configuration and extends the group's understanding by demonstrating that two people could also complete the circuit (lines 13–16). By responding to the questions collectively, the students worked together to come to a fuller understanding of how electricity flows and the different ways that a complete circuit might be constructed. About a minute later, focusing on the digital projection, beginning in line 17, the students observe the movement of electrons around the completed circuit. B2 concludes that the projection shows that electricity is circulating and not static. G then gestures to interact with the device but appears not to fully understand how it works until B1 and B2 demonstrate how the connection should be made. G signals her understanding in line 28 and continues to write down the group's answer.

The next excerpt shows how a different group worked with the bank of previous group answers to check their own understanding. In this excerpt, B1 refers to the boy in the black hoodie, B2 refers to the boy in the white t-shirt, and G refers to the girl.

Excerpt 2 (24:15–26:30)

1. G: ((Reads aloud the response form.)) Others have said…
2. B1: ((Silently follows along and reads the form while G is reading aloud.))
3. B2: ((Gestures.)) Look on that board.

4. B1 and B2: ((Both are looking over at the answer bank.))
5. B1: You are supposed to…
6. B2: ((Walks over to read the board.))

7. B1: Well we should put it in our own words so…
8. G: ((Turns around to look at the board that B2 is reading.))
9. B1: ((Follows over to the board also.))

In this excerpt, prompted by the sentence starter, "Others have said…" one student remembered the bank of previous group responses and directed the rest of his group to use this scaffold. As the students read the answers, there is some brief discussion around which response was "correct" and how to rephrase it in their own words (lines 1–13). As they are engaged in this activity, they evaluate and compare what others have written to what they believe is actually happening in the phenomenon. In lines 15–17, B2 returns to interact with the device to test his understanding once again. G and B1 observe what B2 is doing and the group collectively concludes that the previous responses were correct and that their group also figured it out (line 20). In this way, they are indirectly critiquing their own knowledge for weaknesses in their understanding to strengthen their overall argument.

Both excerpts are fairly representative of the kinds of dynamics that occurred in Condition 4 groups. The excerpts demonstrate how the digital augmentation and knowledge-building scaffolds helped students engage with the scientific content, manipulating the device to help them confirm and/or disconfirm their understanding. We hypothesize that these dynamics that were mediated by the technology and knowledge-building supports

Q1

(5 of inaudible discussion)

10. G: ((inaudible)).
11. B2: ((Points to a response on the board.))
12. G: ((Reading aloud the responses on the board.)) I think that it takes body (heat) to ((inaudible)). ((Reading several responses aloud)).
13. B1: I think we should say…

(2)

14. B1: Other than that, I actually ((inaudible)).
15. B2: ((Goes back to the device and touches all four spheres: two with his hands and two with his elbows at the same time.))

16. G and B1: ((Both walk back to the device and the clipboard.))
17. B2: ((Picks up the clipboard to look at the questions.))

(5)

18. G: ((Reads from the form.)) We agree with them because…((circles something on the form))
19. B1: They were right.
20. G: ((Laughs. Writes.)) This is what we also figured out.

resulted in the differences in C4 students' abilities to theorize at a higher level than students in the other conditions.

Discussion

The results of the conceptual knowledge survey that tested for increases in general knowledge of electrical conductivity and circuits showed that only students in Condition 1 (no digital augmentation) did not demonstrate a significant increase in their understanding after manipulating the device. This finding suggests that the digital augmentation did have an impact on conceptual knowledge, and further supported our results from previous phases of this research (Yoon et al. 2012). The fact that students had the greatest gains in Condition 2 (just digital augmentation and no other scaffolds) suggests that other scaffolds may not have been necessary to increase learning of these general concepts. This conclusion is supported by the fact that a repeated measures ANOVA found no significant differences comparatively between the mean gains of the conditions.

However, the results found increased cognitive abilities in terms of theorizing about the phenomenon from students in Condition 4, suggesting that scaffolds might be necessary to reach more advanced learning. Both findings are consistent with other research. For example, Klopfer and Squire (2008) found that students were able to solve the simple problem, but required additional teacher supports to resolve more complex ones. Similarly, John and Lim (2007) found that although students learned from the medical training augmentations, the learning gains were enhanced when combined with pedagogical scaffolds. There are other plausible explanations for why no differences in learning outcomes between the conditions were found in the conceptual knowledge survey. In research meetings, one researcher on the team discussed the idea that the scaffolds may have overly formalized what was supposed to be an informal experience, e.g., reading response form questions, following directions, and filling them in. This researcher was the main observation field note taker. She recalled that the feeling in the research area was markedly different between the conditions. Students in Condition 2 were generally more playful and experimented on their own—much like students would normally behave in museum exhibits during a school field trip. Students in Conditions 3 and 4, however, were more serious and referred to the questions to dictate their next steps thereby missing the important concepts—much like traditional classroom instruction. Another explanation that may be related to this over-formalization is the fact that students in Conditions 3 and 4 had already spent more time with the device and the post-intervention survey questions were the last thing standing in the way of play in other nearby museum exhibits such as the Sports Challenge. Thus, their rushed responses may not be an accurate indication of what they learned. We have counter-acted this possibility by moving the post-intervention survey implementation back to the classroom in subsequent phases of this research.

As noted above, while there appeared to be no significant effect of the student response form and knowledge-building scaffolds on increasing learning of concepts, students' abilities to generalize from their hands-on experiences, which we have interpreted as cognitive abilities, showed differences across the conditions. The increasing trend in Fig. 4 appears to be related to the number and kinds of scaffolds students encountered while manipulating the device. Students in Condition 4 (with all scaffolds available) were better able to generalize their understanding. Their ability to generalize also appeared to relate to the presence of scaffolds. This finding is relevant to the field of informal science learning in that we provide some evidence that indicates that a modified knowledge-building approach may be useful in helping students learn science beyond simply manipulating and observing phenomena (NRC 2009). Furthermore, through our investigation of a kind of learning design, we believe that this study responds to the call for more systematic research that identifies how learning science in informal science environments can impact the broader goals of STEM education (Rennie et al. 2003).

Although the results for question #2 were encouraging, we were also interested in identifying which scaffolds were most helpful in terms of learning science in the museum. From the interview data analysis, it appears that the findings were mixed. Overall, students identified the ability to collaborate with each other as the most helpful scaffold, which is consistent with other knowledge-building studies (e.g., Yoon 2008) and studies on collaborative learning (e.g., Dillenbourg and Schneider 1995; O'Donnell and O'Kelly 1994). One of the important design constraints that challenged the research team during construction of the condition activities was the notion of deep investigation over an extended period of time that is characteristic of successful knowledge-building classrooms (Scardamalia 2002). We were concerned that the single-visit episodic nature of museum learning experiences would greatly inhibit the ability for students to knowledge build. To be clear, we are not claiming to have achieved knowledge building in this study. Rather, we are addressing the ability to use scaffolds adapted from the knowledge-building literature to promote learning in informal environments. Those scaffolds were represented by the directions to collaborate, the collaboration itself, knowledge-building prompts, and the bank of other group responses intended to stimulate the creation of "rise above" notes. From the interview data, there is evidence to suggest that there is some utility when students are familiar with the terms and processes. However, to ensure that all students receive the intended learning benefits of knowledge building, more time needs to be devoted to learning the terms and processes which would take longer than one activity during a single visit affords. This constraint in addition to our hunches about the over-formalization of informal activities and the increased cognitive skills in the last condition has led the team to conclude that further investigation is warranted.

We also acknowledge that, generally speaking, the students' raw scores and gains for conceptual and cognitive understanding overall were low. In reality, the designed informal science learning experience about electricity in which visitors find "Be the Path" also includes adjacent devices that present similar content—including "Compass Confusion," "Magnetic Maps," and "Circuit Bench." The interaction with all of these devices is intended to have a cumulative impact on understanding. For the purposes of this study, however, we deliberately ignored those other devices as our focus was on the comparative impact of the digital augmentation and knowledge-building scaffolds for "Be the Path." We hypothesize that a longer time on task with extended experiences on similar devices will improve this outcome.

Conclusions and future research

Results of the study continue to support our finding that digital augmentations can help in conceptual development of science knowledge, serving as an important scaffold in and of themselves for learning during an informal science experience. This study's findings also suggest that ability to theorize from the museum experience can be improved through the use of knowledge-building scaffolds such as response forms and the ability to work in groups. While students unanimously said that collaborating in small groups was helpful and a majority of students said that the response forms were helpful, the utility of the other scaffolds is inconclusive. In the next phase of this research, we have made the following modifications in order to probe more deeply. For Condition 4, since it was not clear that all students had actually read the printed group work directions, they will be read aloud in order to guide their behavior. Rather than a suggestion, students will be required to consult the bank of previous answers before they construct their own. Students will also be instructed briefly about what the knowledge-building prompts mean and, finally, the post-intervention surveys will be administered the day after their museum visit rather than immediately after the activity. To address the issue of over-formalization, another condition will be added between Conditions 3 and 4 in which we will post the response form questions but with the directions, knowledge-building prompts, and the bank of previous group answers added. In this condition, students will also work in small groups but will not be required to fill in the form while they are interacting with the device.

Considering the difficulty inherent in reconciling the time and facilitation required to establish and maintain a true knowledge building environment with the paucity of time spent with a given device by the average science museum visitor, the results of this study open the door for further opportunities to adapt knowledge-building scaffolds to fit the informal learning environment. We are hopeful that our team and other researchers will be able to build on these results with larger numbers to contribute to our collective understanding of how computer-supported collaborative learning can best be supported in informal environments.

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