Design Conjectures for Place-Based Science Learning About Water: Implementing Mobile Augmented Reality with Families

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Abstract: From a design-based research study with 31 families, we share the design conjectures that guided the first two iterations of research. The team developed a mobile augmented reality app focused on water-rock interactions to make earth sciences appealing to rural families. We iterated on one design element, the augmented reality visualizations, to understand how these AR elements influence families' learning behavior in a children's garden cave as well as their resulting geosciences knowledge. This analysis is an example of how design conjecture maps can be used to support research and development of mobile computer-supported collaborative learning opportunities for families in outdoor, informal learning settings.

Water is a critical resource in communities, which recent environmental and health crises have demonstrated that people have questions about safeguarding. For instance, families in urban communities such as Flint, Michigan and rural families in areas where natural gas is being extracted by fracking have concerns about the safety of their drinking water. As researchers have begun to study water education, ethnographic approaches have been taken to understand the impacts in classrooms related to learning and social justice (i.e., Davis & Schaeffer, 2019) and the effects of generational differences in environmental understanding on school-based learning (Zimmerman & Weible, 2017). Our team joins these efforts to support learning about a community's water through conducting design-based research on family-based water education for out-of-school time.

We investigate how immersive experiences for families, using mobile augmented reality (MAR)**,** create meaningful science learning experiences. We designed a MAR app that allows families to see the unseen water-rock interactions that historically shaped and currently influence their community. We report on the first two iterations of research with a MAR app in order to draw design implication to support future work. Our approach builds from research about the scientific practice of observation (Eberbach & Crowley, 2009; 2017), and research on AR to make "the invisible science visible" in museum exhibits (Yoon & Wang, 2014).

Theoretical framework

In our design-based research project, we engage learners to see the unseen water and rock interactions in their community by supporting the **science practice of observing**. Eberbach and Crowley (2017) suggests that learning to conduct scientific observation is difficult—coordinating disciplinary knowledge with what one notices is a practice learned over time. Observing and explaining requires support (Land & Zembal-Saul, 2003; Eberbach & Crowley, 2009; Smith & Reiser, 2005). Informal learning research has shown that parents guide youths' participation by generating interest and collaboratively building knowledge (Zimmerman, Reeve, & Bell, 2010; Crowley & Jacobs, 2002). Our design relies on parents to guide interactions based on prior work that showed children learn science more deeply when assisted by an adult (Fender & Crowley, 2007). Given the challenge of scientific observation, we draw upon place-based science education. Place-based science education concentrates on learners' meanings of place to develop design strategies that are scientifically-sound and culturally-appropriate, most often via on-site fieldtrips or fieldwork (Semken, 2005). Place-based science education considers places as more than geographic locations associated with one specific time; place includes geographic, temporal, ecological and sociopolitical elements (Lim & Calabrese Barton, 2006).

Eijck and Roth (2010) argue science education must reflect the multiplicity of meanings of a place held by dominant and non-dominant cultural groups. With place-based approaches, Semken focused on indigenous physical geology (Tsé na'alkaa), while others focus on agriculture (Membiela, DePalma, & Pazos, 2011), ecology (Marin & Bang, 2018; Zimmerman & McClain, 2014), and urban (Tzou, Scalone, & Bell, 2010) and rural (Avery & Karim-Aly Kassam, 2011) issues. Increasingly, water quality is phenomena of interest in science education. Shepardson, Wee, Priddy, Schellenberger and Harbor (2007) studied conceptions of watersheds held by 915 students from 25 classrooms through a draw-a-watershed protocol. The study concluded that rural students had deeper understandings of watersheds than did urban or suburban learners (whose knowledge drew primarily upon textbook representations of watersheds, rather than lived experiences). Through ethnographic research in Appalachian counties, Schafft and Biddle (2015) found that, although not formally part of the school curriculum, the socioeconomic issues around water entered schools as adolescents decided whether to pursue the transient, but high-paying, jobs in the natural gas sector. Placed-based science education evokes emotions (Jaber & Hammer, 2016), and water education can evoke anger and distrust (Davis & Schaeffer, 2019).

Our inclusion of a MAR app is based on contextual mobile computing (i.e., Sharples, 2010). Mobile technologies support playful science observations in outdoor settings, such as woods (Rogers et al., 2004), gardens (Zimmerman et al., 2015; Huang, Lin, & Cheng, 2010; Zuiker & Wright, 2015), watersheds (Kamarainen et al., 2013), and trails (McClain & Zimmerman, 2014; Tan & So, 2011). Specifically, we adapt the definition of Georgiou and Kyza (2017) that AR fuses digital layers from various media within a physical setting in such a way that learners remain immersed in a hybrid MAR-real-world setting.

Finally, our perspective on learning includes supporting conversations. We consider families' conversations as learning processes *and* learning outcomes. In conversations, learners integrate knowledge to engage in sensemaking (Linn, 2002; Zimmerman, Reeve, & Bell, 2010). Sensemaking occurs when families jointly construct meaning as they integrate prior experiences, material resources, and new knowledge. Through sensemaking, learners create disciplinary and personal significance as they talk. Conversational sensemaking is often considered the primary learning process in informal settings (Bell et al., 2009).

Methods

Our analysis addresses the following research question: *How do the designed elements of a MAR app support families' engagement in disciplinary observations and talk about a water and rock?* As such, we adopted design-based research (Sandoval & Bell, 2004) methodology—an iterative, mixed-method approach that relies primarily on qualitative analyses. We answer this question by first creating a design conjecture map (Sandoval, 2014) to articulate the relationship between the elements of the app, the families' resulting mediating processes on-site, and the resultant learning outcomes. In this analysis, we focus on one app element (AR components) and the mediating processes based on analyses of video data from 31 families using an app on caves in a children's garden and from 29 matched pre- and post-visit answers to the driving question of, "How do caves form?"

Arboretum setting: Cave in a children's garden

The Arboretum has a pollination garden, children's garden, live specimens, sculptures, and various scientific representations—all common exhibition genres found in outdoor learning spaces. We focus on the children's garden, which was built specifically around regional hydrogeologic landscape, wildlife, and botany. Our current analysis focuses on a MAR app we developed to augment a full-size simulated cave (capable of holding 30 people) within the children's garden, which includes stalactites, stalagmites, columns, bat sculptures, a play sandpit, a live barn swallow nest, and two ceiling openings. The cave evokes the sensory experience of being in an actual limestone cave through careful selection of natural materials, lighting, stalactites/stalagmites, and the inclusion of slow drips of water. No educational or interpretive signage is present inside or near the cave.

Family participants

Across two iterations of research, 33 families participated. Of these, 31 families completed the tour with their video and audio intact. Families included at least one child in the age range 4-12. A parent or legal guardian had to be present to consent each child into the study. Multigenerational, mixed-age-sibling, and multifamily groupings were common. Data analyzed here are from 14 families in Iteration 1 and 17 families from Iteration 2.

Data collection and analysis

We collected complete data from 31 of the 33 families. The primary data sources are GoPro® point-of-view video cameras worn by at least one family member and iPad mini® screen recordings that captured voices and app interactions. Secondary data sources were the pre- and post-experience responses to the driving question (how are caves formed?). Other data included (a) digital photographs that were captured and annotated by learners during the experience, (b) demographic surveys that included zip code, race/ethnicity, school attended, occupation, age, and prior garden and cave visits, and (c) post-experience interview (three questions; 3-5 minutes per family).

Given our goal to design for tablet-supported collaborative learning for outdoor spaces, our analyses have a social unit of analysis — each family is one learning group. Before our analysis, a family's GoPro video was synchronized with their iPad screen recording. These videos were professionally transcribed and then confirmed by researchers. First, all authors watched one-third of the videos together with an interaction analysis framework (Jordan & Henderson, 1995). The team engaged in open-ended discussions of behaviors and discourse. Second, we coded the videos based on the conjecture map in Figure 3 with a focus on AR elements and learners' mediating processes. Finally, to understanding learning outcomes, we coded video transcripts of the families' pre- and post-visit answers to the question: "How do caves form?" To analyze learners' questions, we adapted Eberbach and colleagues' (2012) codes for conceptual coherence. Verbal responses were scored: (1) Level 1-

mentions one component of a concept; (2) Level 2 - attempts an explanation, but either is not fully correct or uses scientific vocabulary in explanation without describing the process; and (3) Level 3 – gives detailed explanation that describes underlying concept. The frequency of these responses was tallied and compared. Inter-rater reliability was good for both the pre-tour total (ICC = 0.81) and the post-tour total conceptual score (ICC = 0.82).

SPACES: MAR technology designed for families

For our intervention, we digitally augmented the cave with scientific representations and resources that expanded what can be observed on-site. We designed a MAR app (*Figure 1*) for collaborative learning about caves and hydrogeological phenomena during 15-minute self-guided walking tours. The app included AR visualizations that were developed using Apple's *AR Kit*. All digital images, animations, and text were based on helping families answer the driving question of *how do caves form*. The AR elements support physical observations within the cave. In past AR efforts (Zimmerman et al. 2019), we used iBeacons, QR codes, or learner photo capture to trigger the AR content. In this MAR app, learners launched contextually-relevant 2D AR content (images, animations, and text) and an AR photo capture tool. We also used markerless 3-D object recognition to trigger 3-D animated AR content that was superimposed into the cave space when holding up the iPad (i.e., a column forming from a stalagmite and stalactite virtually appeared in the space; dripping water entering the cave was virtually superimposed onto the cave ceiling). GPS detected the site location to trigger available learning tours.

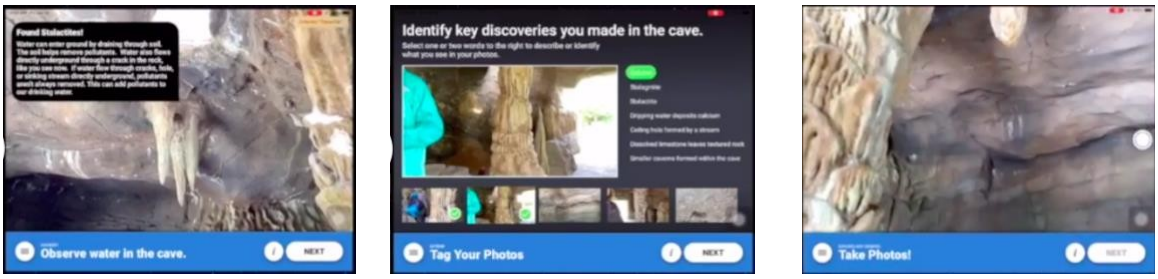

Figure 1. Screenshots that show the AR trigger detected (left), annotating photographs (middle) and the photo- taking screen through an AR browser (right).

Pedagogical model informing the MAR app task structures

The app design was based on a pedagogical model of building understanding from observations (*Figure 2*), using photos as observational data. The app had four phases: (1) explore and take photos of water and rock interacting, (2) learn about hydrogeology with augmentation that included text and visuals (e.g., how stalagmites and stalactites form, how water flows underground), (3) extend thinking by applying new knowledge by annotating photographs taken in phase 1, and (4) connect to your community, which was a water conservation message. The learners could only unlock new activities after completing one phase. Overall, the app had an immersion goal to make the users feel as if they were cave explorers. Iterations 1 and 2 used the same pedagogical model and content on the karst hydrogeology, cave, and sinkholes. Iteration 2 streamlined text and animations (i.e., shortened) with some features altered to allow users to more easily access the 3-D animations that were triggered by 3-D objection recognition (as described below in the results and findings section).

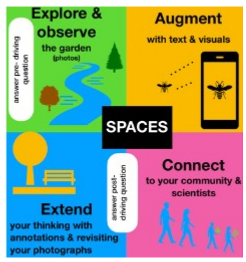

Figure 2. Pedagogical model.

Design conjectures guiding our research and development efforts

Sandoval (2014) suggests that DBR analysts use design conjectures to articulate the relationships among an intervention's components, learners' behaviors during the intervention, and learning outcomes at the project's end. Conjecture maps can be used to interrogate an intervention successfully: did the components work to support learning as designed? In our study, we used a design conjecture map to predict how our mobile AR app would be used by families to learn about hydrogeology (*Figure 3*). In this analysis, we focus on the bolded boxes: the visualization AR tools, the first four mediating processes, and the first outcome of geoscience knowledge.

Iterations 1-2 of the first 15-minute AR tour on water-rock interactions

Our DBR study includes two iterations of the 15-minutes of AR cave tour; two other 15-minute tours related to water-rock interaction over geological history and the local watershed systems are planned for the same garden to enhance the water education experience. Families eventually can choose to do the three tours at once or as three separate visits to the children's garden to reach our goal of place-based science education that attends to a multiplicity of meanings for place. The iterations described here include a MAR app with these features: an orienting AR photo-taking and annotation task, one 2-D animated video describing how caves form, multiple text AR augmentations, two 3-D animated cave features that appeared virtually within the cave through the iPad viewfinder, one short 2-D animated video that contained a stewardship message, and two discussion prompts.

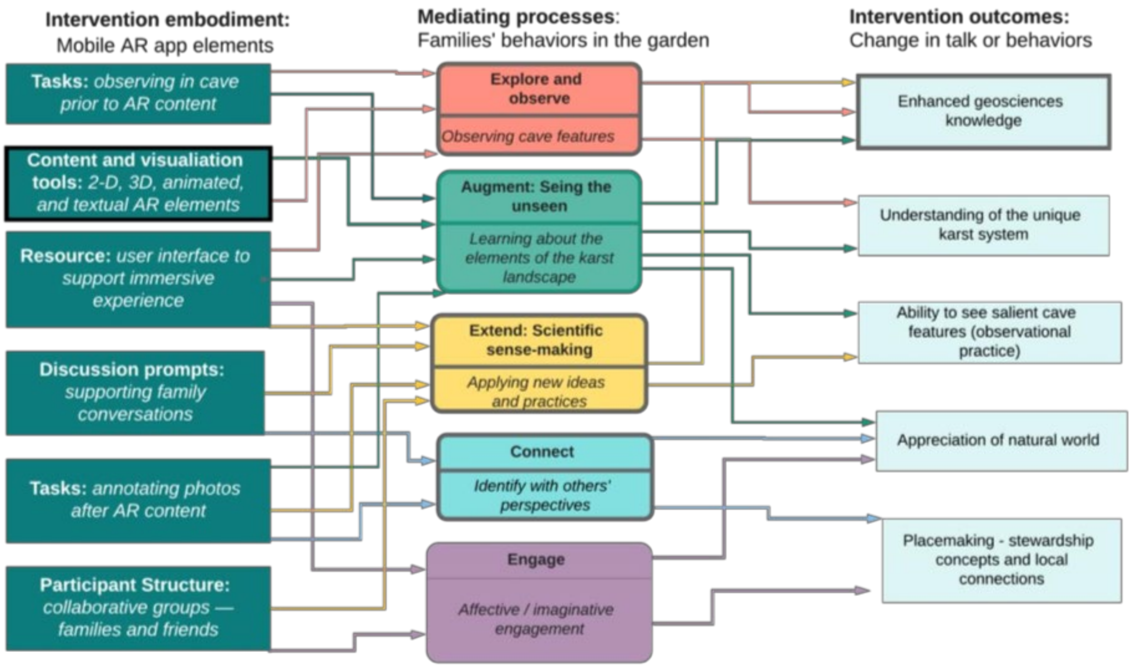

Figure 3. The design conjecture map that guides our research efforts. The elements of our intervention are to the left, with the learning processes in the center, and the resulting learning outcomes to the right.

Given we are at the beginning of our project, we iterate on only one aspect of our intervention embodiment: *the AR content and visualization tools*. The changes include (a) a reduction of text from Iteration 1 to 2, (b) shortening of video length, and (c) changing of how the markerless AR triggered for the two, 3-D animated cave features. The AR trigger for the 3-D feature for both iterations used object-based visual recognition (i.e., large cave features in the cave) rather than QR codes, GPS, or beacons. This enabled us to deploy AR content without needing to install markers into the space. Iteration 1 used a small red notification and black box to notify users that the 3-D object trigger had been detected; this was ineffective to support learners to scan the objects on-site. (Between Iterations 1 and 2, we tried a usability test of AR silhouettes of the trigger object to help families scan the object; this technique proved to be unsafe because the learners would walk backwards to line up the silhouette without looking behind them — ignoring other visitors, visitors' backpacks, and other designed objects in the space.) Iteration 2 used an AR trigger with a more prominent notification that the object was scanned successfully; it also removed text information blocking a full view of the animated AR objects that were layered virtually into the cave. (All 2-D AR elements were triggered by the learners selecting the "next" button.)

Data and results

Our analysis focuses on how one intervention element (the AR tools that provide content and visualization) influenced four mediating processes and one learning outcome (*Figure 3*), as described below. Overall, we found all 31 families who completed the tour were able to navigate the app to collaboratively observe key cave features and share what they learned about hydrogeological phenomena through talking, pointing, gesture, or other body movement. The remainder of this section provided details on how the app mediated their engagement on site in four ways and on the learning outcome of geosciences knowledge.

Exploring and observing mediating process

The families who completed the tour used the app successfully to observe salient hydrogeological features in the cave. On average, the 31 families took six photographs in the cave and later annotated four of these with the vocabulary of the karst hydrogeology system provided by the app.

In one instance of observing while taking photos with the AR browser that was typical of families with older elementary children, a family (mother aged 40, daughters aged 9 and 7, son aged 4), moved around the cave and collaboratively found observed water and rock interacting to form cave features.

9-year-old daughter: Let's take a picture of the dripping.

Mother: Where's the dripping?

9-year-old daughter: See the drip? Right up there? ((pointing))

Mother: Up there? ((pointing)) Oh, yes.

The family above identified water, stalagmites, and other features common in limestone caves. During the activity, while the mother was holding the iPad, she asked her daughter for input on what photos to take. Similarly to nearly all families in our dataset, they used gesture (i.e., pointing) and information about limestone caves provided in the app to successfully identify existing cave features (stalagmites) and water dripping forming new features. The use of vocabulary was mostly present with older children (between 7-12).

Another family illustrates how families with younger children (mother aged 38, sons aged 6 and 2, daughter aged 4) observed water-rock interaction without fully adopting the cave vocabulary.

6-year-old son: Yeah, because I think there used to be a big hole right there and then all the — and stuff interacted with the water to make this.

Mother: Okay, come here let's take the picture. ((younger child splashes in water))

This second family's interactions demonstrates that together they were able to observe key phenomena and showed their understanding through interactions with the setting (splashing in water and pointing), but they did not always adopt the scientific vocabulary presented in the AR materials. In some cases, the families with younger children relied on pointing (or other gesture) to communicate their meanings.

Seeing the unseen mediating process

All 31 families were able to engage with the 2-D AR content for seeing science concepts that were not visible without an expert perspective; however, some families experienced difficulties using a 3-D object as a markerless AR trigger — meaning that they had problems finding the optimal location to scan an object for the 3-D animated AR materials to launch. However, with help triggering the AR, most families observed at least one phenomenon related to karst systems: the formation of columns over thousands of years and water moving through caves.

As families were supported in scientifically observing cave features, they collectively participated in sensemaking. Much dialog showed evidence of "epistemic affect," a key aspect of engagement in a scientific discipline (Jaber & Hammer, 2016). Here, an 11-year-old daughter not only highlights the AR animation to her sisters, but also shares her understanding of the geologic process.

11-year-old daughter: ((viewing AR column)) Oh! That is cool! Whoa. Hey [8-year-old name], look at this. [Name] come over here and look! [Name] look. It's growing, it's growing.

8-year-old daughter: What is?

11-year-old daughter: They're growing together. Now, it's another column.

Affect indications are apparent as 11-year-old experiences and makes sense of an augmentation with the AR app. This kind of collective epistemic affect moments (e.g., sharing surprising and interesting observations with each other) were common among mix-age siblings.

Extending scientific sensemaking to the karst system mediating process

Caves in karst hydrogeological landscapes include limestone rock, water that has been exposed to carbon dioxide in the air or soil to make acidic water, and the dissolving or eroding of the limestone rock by the acidic water, while sandstone rock stands over time to create ridges (i.e., small mountains). Through our atlas.TI-supported analysis, we found that some of the learners began to make sense of the complex karst system together.

7-year-old daughter: Mommy, look, a stalagmite! ((pointing))

Mother: See stalactites and stalagmites. They're in limestone caves.

Daughter: Mommy, look it's another stalagmite! ((pointing))

Mother: Yes!

Here a daughter points out key features in the cave and the mother used information from the app to talk about the cave they were in was specifically, a limestone cave.

Connecting to the place mediating process

During the tour, families not only paid attention to the geological features of the cave, but they also made temporal and ecological connections to the place and the larger local environment.

Mother: It says, "Cave features form slowly, only adding four inches in one thousand years." How long do you think four inches is here?

9-year-old daughter: ((counts out the length of the stalagmite, approximating an inch with her fingers)) One thousand. Two thousand. Three thousand. Four thousand…Twelve thousand. About thirteen thousand years old!

Mother: What? That is crazy.

The 9-year-old daughter used her body to situate herself in and to connect to the cave by exploring the temporal element of the place. The cave, in this case, was more than a location but a place constituted of time and history.

Only 11 out of 31 families (35%) discussed the stewardship discussion prompt presented in the water conservation video near the end of the MAR experience. The prompt challenged families to think of ways to protect water in their community. Many families who did not discuss the prompt read the prompt aloud as if the question was part of the video content. For the families that discussed water stewardship, place was an aspect of their conversation. Local streams, rivers, and lakes were named to make the abstract idea of water stewardship concrete to community level concerns. While the team is encouraged by those who made community connections, enhancing water stewardship is an area for further development in the next iteration of the app.

Enhanced geosciences knowledge learning outcome

In this analysis, we focus on one learning outcome: geosciences knowledge. Prior to the MAR experience, many families had visited caves. However, when discussing how limestone caves formed at the start of the visit, few could articulate the water-rock interactions present in karst landscapes. During the visit, families used specific science concepts in their conversations, specifically related to how when water in a karst system mixes with carbon dioxide, acidic water is formed, which can dissolve limestone leaving caves and sinkholes.

Results from our pre- and post-visit analysis of the learners' explanations showed a positive learning gain related to concept coherence of basic regional hydrogeology through a paired-samples t-test. A significant difference was found between family explanations about how caves form pre-visit ($M = 1.8$, $SD = 1.9$) and post visit ($M = 2.5$, $SD = 1.7$); $t(29) = -2.06$, $p = .048$, with a small practical significance suggested by Cohen's effect size value ($d = 0.38$). To examine whether the two app iterations influenced learning gains differently, differences in learning gain means for Iterations 1 and 2 were examined through an independent samples t-test. For this analysis, learning gains were operationalized as the difference between the pre- and post-visit explanations as measured by conceptual coherence ratings. No significant difference was found between Iteration 1's learning gains ($M = .615$, $SD = 1.56$) and Iteration 2's learning gains ($M = .813$, $SD = 2.17$). This non-significant, but positive trend, suggests that the reduction of text and shortening of the movie time did not negatively influence learning and perhaps may have supported learners in the 15-minute tour. Our future work will assess learners after multiple tour experiences to better understand the impact of the MAR experience over longer timeframes.

Discussion and significance

Our findings showed that our AR app supported families' talk and interactions through four mediating learning processes. Many families were able to engage in discourse about how caves are formed in their region, which holds promising implications for designing short-term, technologically-augmented experiences for science observations. In additional to the mediating process data from conversations, our quantification of the pre- and post-tour explanations showed a small, positive gain of conceptual understanding from the 15-minute experience.

The families' science talk and gesture in the simulated cave adds to the understanding of how to integrate context-sensitive technologies to support scientific observation via informal science, place-based learning experiences. Place-based goals were met; however, only for one-third of the families in our dataset. More work on supporting stewardship and community connections through AR will be investigated in future iterations.

Similar to previous research findings showing the pervasiveness of technical usability issues with AR learning experiences (Akçayir & Akçayir, 2017), we also found that the novel inclusion of markerless 3-D object-oriented AR was a challenge for families to learn how to use in this short experience. Future research will explore strategies for mitigating the technological issues for families to launch AR content using 3D objects as triggers.

Given the importance of place-based water education, Iterations 1 and 2 of our research provided a baseline for future work. For next steps, we will incorporate Jensen's (2010) four kinds of meanings that learners develop from successful environmental education programs — knowledge (a) about an environmental problem, (b) of the cause(s) of the problem, (c) about individual and/or collective strategies to solve the problem, and (d) about future alternatives and new perspectives. Jensen argues that environmental learning can improve the lives of people by encouraging environmentally sustainable actions ─ yet often educators do not teach environmental topics in a way to foster knowledge that leads to sustainability actions. Relatedly, Kollmuss and Agyeman (2002) found that extensive education about environmental issues increased student knowledge about the content, but increased knowledge was not always correlated with increases in students′ pro-environmental behaviors. We will build on this perspective of action-oriented learning to support stewardship by considering how future iterations of our app can support knowledge of hydrogeology as well as new individual and collective sustainability actions taken up by families as learning outcomes.

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Acknowledgments

This project was made possible in part by the National Science Foundation, grant #1811424. The views, findings, conclusions, or recommendations expressed in this article do not necessarily represent those of the National Science Foundation.