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Mobile Augmented Reality Supporting Community-based Learning: Families' Exploration of Land-Water Interactions

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Abstract: From a design-based research study investigating rural families' science learning with mobile devices, we share findings related to the intergenerational exploration of geological time concepts at a children's garden at a university arboretum. The team developed a mobile augmented reality app, *Time Explorers*, focused on how millions of years of rock-water interactions shaped Appalachia. Data are recorded videos of app usage and interviews from 17 families (51 people); videos were transcribed, coded, and developed into qualitative case studies. We present results related to design elements that supported sensory engagement (e.g., observation, touch) through AR visualizations related to geological history. This analysis contributes to the literature on informal learning environments, theory related to learning-on-the-move, and the role of sensory engagement with AR experiences in outdoor learning.

Understanding the scale of earth sciences scientific phenomena, such as geological time, is often difficult for learners (Cervato & Frodeman, 2012; McDonald et al., 2019). Geosciences educational researchers and educators (e.g., Orion & Ault, 2013; Resnick et al, 2017; Tretter et al, 2006) have used pedagogical techniques such as analogies, walking or moving through a scaled version of a time or space, or time-lapsed videos to address these challenging concepts. Additionally, the environmental crises that overlap the earth sciences, such as water quality and freshwater access, are complex— requiring understanding and solutions that integrate information across various geographic, geological, and time scales. To address these difficulties in learning earth sciences concepts, our team has been developing mobile, augmented reality (MAR) apps deployed on handheld computers (iPads, iPhones) to support rural families to learn these complex topics in outdoor spaces in their communities. This analysis focuses on one app, *Time Explorers*, that addresses geological time with an immersive MAR experience that illustrates how millions of years of rock-water interactions shaped one Appalachian community.

MAR layers digital material into outdoor spaces via devices' screens to expand opportunities for learning (Ryokai & Agogino, 2013; Zimmerman et al, 2020). MAR relies on digital resources to reveal scientific meanings not directly visible to learners (Dunleavy & Dede, 2014) in parks, gardens, and forests (Georgiou & Kyza, 2017; Kamarainen et al., 2013; Land & Zimmerman, 2015). Our immersive MAR designs focus on developing *micro-sites* (Sharples & Pea, 2014) for families' learning —drawing upon planned and emergent experiences to create science learning opportunities related to geological topics. In this paper, we ask the research question:

- How does a MAR app influence families' sensory engagement related to understandings of geological time in an informal learning environment as they participate in an immersive learning-on-the-move experience to understand the effects of millions of years of land-water interactions?

Conceptual Framework: Learning-on-the-Move and Sensory Engagement

Geological time is foundational to understanding the geosciences as it "highlights the way geoscientists tell time – a coarse time scale in which millions of years are the most common coins of currency" (Cervato & Frodeman, 2012, p. 3). Earth's geological time can be determined by observations and analyses of rock strata and the fossils the strata contain. Cervato and Frodeman (2012) point out numerous reasons that learning geological time is difficult for learners including that learners mistake the timing of key geological events (e.g., formation of mountains, landform movements), confuse the timing and distance between geological periods, and have limited understanding of the rate of erosion, deposition, and landform movements. Our research and development efforts on a MAR app influence brought together two key concepts to first design for and then analyze families' sensemaking about geological time: a) learning-on-the-move to illuminate the change in time metaphor of the app and b) sensory engagement (e.g., visual, tactile) to observe evidence of the past in the rocks and the simulated cave and rock strata on-site.

Learning-on-the-Move to Support the Understanding of Scale

Researchers study the use of mobile technologies in and around communities via the concept of learning-on-the-move (LOTM) (Marin, 2020; Silvis et al., 2018; Taylor, 2017; Zimmerman, & Land, 2022). LOTM describes a social learning process where people collaboratively learn as they move their bodies within and through spaces.

Movement, especially gesture, has been found to be a supportive sensemaking approach in science and mathematics education (e.g., Alibali & Nathan, 2012) —including with technology (Kang, et al., 2021). Looking at movements within and across spaces, Silvis et al. (2018) investigated families' technology practices and found that mobile computers and other technologies were integrated as learning tools across sites. Taylor (2017) used ethnographic methods to explore how youths used mobile technologies, on foot and by bicycle, to understand their community as a designed, complex system.

In our case, we designed for LOTM, where people's movement enhanced our immersive time travel narrative and encouraged sensory engagement with the specimens and sculptures in a garden. Drawing from Ma (2017) who considered large-scale "multi-party, whole-body interactions" as critical in learning geometry, we designed learning experiences for families, whereby moving their bodies through a children's garden together, leveraged multiple body-place interactions to make sense of geological time. Relatedly, we built our research and design efforts from Marin's (2020) assertions that " walking and lands/waters have always been and continue to be central to human learning, development, and activity (p. 282)." Marin and Bang (2018) found questioning, directing, and narrating were key learning practices that families used to make sense of the natural world, and as such, in our designs, the team left space for families' conversations to allow for learning practices to emerge.

Sensory Engagement to Support Scientific Observations

Beery and Jørgensen (2018) note that when children play outside, their physical play includes body movement and sensory engagement. Ballantyne and Packer (2009) argue that sensory engagement is an essential part of learning in environmental education experiences. From McClain and Zimmerman (2016), we define sensory engagement as gestures and movements that foster visual, auditory, and tactile observations and gestures that create joint attention (i.e., pointing) and discussions.

Sensory engagement (through visual and tactile means) supports scientific observation (Eberbach & Crowley, 2009). Mogk and Goodwin (2012) argue that learning to observe is critical for the geosciences: "Observations in the field allow us to interpret and explain what has happened in the past (postdiction) in order to show us what is possible regarding present and future Earth phenomena (prediction)" (p. 141). We focus on sensory engagement in our study, as primarily tactile and visual observations. This includes the learners comparing the texture of sandstone and limestone rocks, feeling for marks of erosions, and observing rock layers and how they can move over time.

Method: Two Iterations of Design-Based Research

We use the iterative, qualitative approach of design-based research (DBR) approach (Sandoval & Bell, 2004). DBR advances theory related to LOTM and sensory engagement as it enhances practice related to the design of informal learning environments.

Participants and setting

Our study focused on rural families visiting the children's garden at the Arboretum at Penn State. We utilized our community partners' websites, social media sites, and listservs for recruiting. All participating families required internet access to complete online consent and participate in our Zoom interviews. We acknowledge that we only reached rural families with ample technological resources during COVID-19.

In Iteration 1, seven families living in two rural counties participated (8 adults, 12 youths). Guardians self-reported their families' racial affiliations as White (100%); two children were also guardian-reported as Other (10%). Children (female: 25%, male 75%, non-binary: 0%) were primarily 5-12 years old (92%). Two guardians were scientists; two were administrative staff. Other occupations were writer, farmer, and educator. One family homeschooled their children. In Iteration 2, ten families living in one rural county participated in the research (15 adults, 16 youths). Guardians self-reported their families' racial affiliations as mostly White (White: 97%, Black or African American: 3%, Hispanic or Latinx Origin: 3%). Children (female: 50%, male 50%, non-binary: 0%) were primarily 5-12 years old (94%). Four guardians were educators (e.g., teachers, instructors, professors); three were unemployed; and others' occupations were researcher, program specialist, homemaker, human resources staff, illustrator, CFO, self-employed, and military. Two families homeschooled their children.

Time Explorers app features and technology

The *Time Explorers* MAR experience was approximately 20-40 minutes as families completed a narrative time travel journey through the geological history of Appalachia in the children's garden. *Time Explorers* was divided into eight micro-sites organized by geological time (starting at prehistory). Guided by the GPS map, learners moved forward in time to understand how vital landforms of the area were formed in Appalachia: (a) Time Spiral (Ordovician Period), (b) Coral Sculpture, (c) Limestone Boulders, (d) Sandstone Boulders, (e) Arched Rock Wall,

(f) In-and-Out Creek, (g) Cave, and (h) Spring Basin (Figure 1). In Iteration 2, the MAR elements were the same; however, we added an AR filter family selfie at the end of the experience, a back button, made simple text edits for clarity, fine-tuned the GPS for the cave micro-site, and added a pre-interview task.

Figure 1

Flow of the Time Explorers app designed for the children's garden at the Arboretum at Penn State. Note: the AR Filter Congratulatory Selfie was added in Iteration 2.

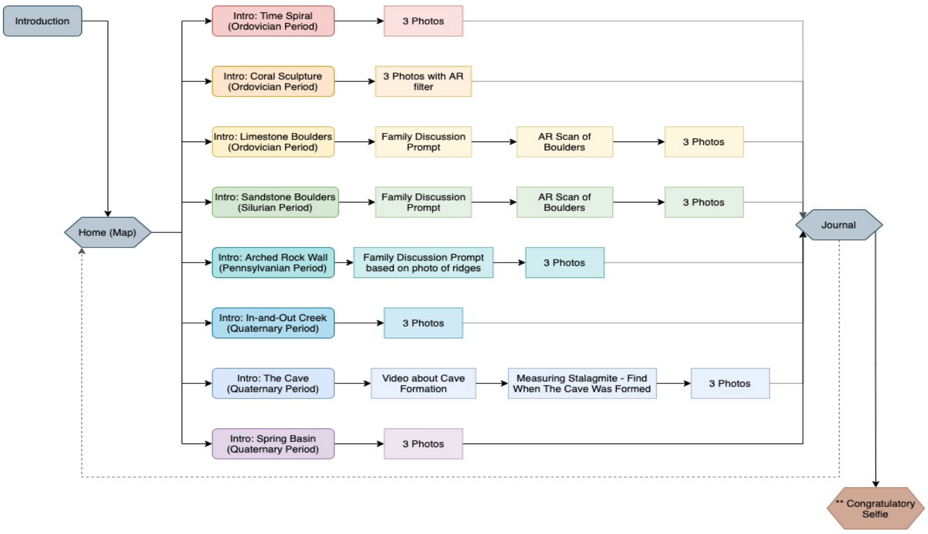
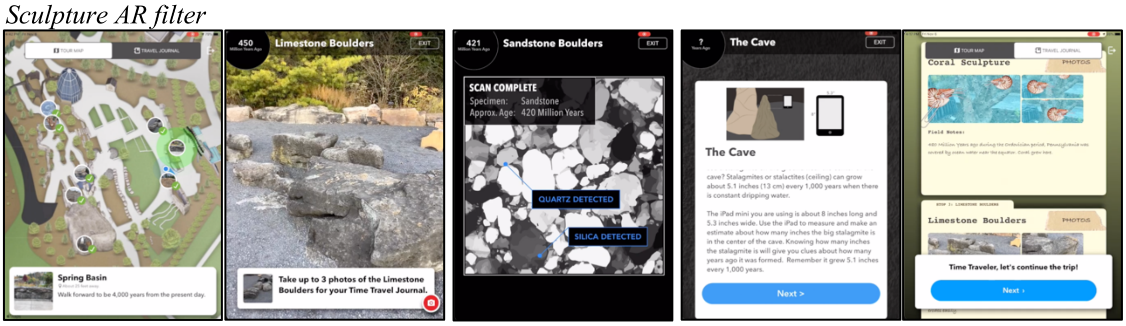


Figure 2

Screenshots from Time Explorers: a) GPS map showing completed and next micro-sites, b) photo-taking activity, c) sandstone boulder AR scan, d) Cave measuring activity, and e) travel journal with the Coral Sculpture AR filter



(2a) (2b) (2c) (2d) (2e)

Data sources and analysis

Due to COVID-19, our data were collected with a social distancing protocol. Data include 16 families' iPad screen recordings and GoPro videos that captured their talk interactions in the MAR learning experience. One family's GoPro video and four families' screen recordings were not fully captured due to technical difficulties. Families borrowed one iPad with the *Time Explorers* app, which recorded their app interactions and talk throughout the experience. One family member wore a hat-mounted GoPro camera to record the experience in the first-person view. The screen recordings and GoPro videos were displayed side-by-side for data analysis. Additional data included 17 pre- and post-experience interviews via Zoom and 17 online demographic survey responses. In Iteration 1, the pre-experience interview included questions on how ridges, valleys, and caves formed and if the family had prior experience with caves. The post-experience interview included a) the same two questions, b) a drawing task which asked the oldest child to draw how ridges, valleys, and caves formed, and c) the family's overall impression of the app. In Iteration 2, we also included a) the drawing task in the pre-experience interview, b) questions related to how caves formed and how water shaped the landscape, and c) one question on whether the family had ever seen similar landforms. The drawing task was completed by the families' eldest child (with any younger children having the option to also complete a drawing). The eldest child explained the drawings first, followed by a family discussion.

To analyze how families used sensory engagement and learning-on-the-move to make sense of the geological prehistory, we conducted a qualitative analysis of the screen recordings (thirteen whole and two partial) and GoPro videos (sixteen full) at the unit of analysis of the family (defined for our study as at least one guardian and one child aged 5 to 12). To conduct interaction analysis (Jordan & Henderson, 1995), the authors held co-viewing sessions to watch all screen recording and GoPro videos together (after the videos were professionally transcribed). Codes were applied to the video records by two authors to compare and contrast the families' experiences. Based on the IA session notes and coding spreadsheet, we selected three cases on how the MAR app influenced sensory engagement for this manuscript. To further analyze the three focal cases, a line-by-line analysis of the transcripts occurred, which highlighted how families' sensory engagement (verbal or tactile) was connected to verbally stated observation of hydrogeological phenomena or explanation of geological history at each micro-site. To understand the three case study families' learning outcomes, the drawing tasks from each family were analyzed to understand any changes in learning of water-rock interactions over geological history. Finally, to enhance our data analyses' trustworthiness, the team conducted co-viewing sessions, shared notes, and multiple researchers double-checking transcripts and codes.

Results

Overall, the families who engaged with *Time Explorers* successfully navigated through the learning-on-the-move time travel metaphor to move their family through the garden on a time walk from the Ordovician period to the present day. Families started at the time spiral and had an app image that moved them through key landforms that represented different periods of geological time, used the app resources to place the landforms in their appropriate geological time, and engaged in sensory engagement (primarily tactile and visual observations) to support their understanding of the formation of the Appalachian landscape.

Case study 1: MAR app supported sensory engagement without being a distraction

Given the digital technology, our team examined if our MAR materials supported geosciences-related observational engagement in the children's garden without distracting the families. We found the mobile computers did not dissuade families from engaging with sensory exploration in the outdoor learning space. During the AR experience, Tanya (Mother) and Oliver (11-year-old boy) engaged in sensory observations of the features representing the landforms. For example, at the Sandstone Boulders, following the display of a prompt, the family walked closer to the rock and touched it:

Tanya: What do you see? ((touches sandstone))

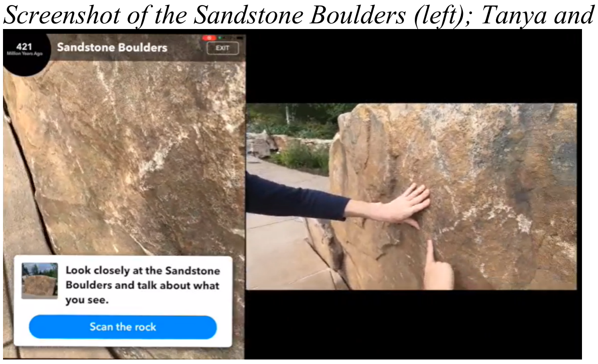
Oliver: It's smoother, and it's flatter than the other one [refers to Limestone micro-site] ((touches sandstone)). It has little dents in it. (Figure 3)

Tanya: They are picked apart in some areas ((moves a finger to an indent)). Feels bumpy and almost like sand a little bit, right?

Oliver: Mhmmm (affirmative). ((touches the indent))

Figure 3

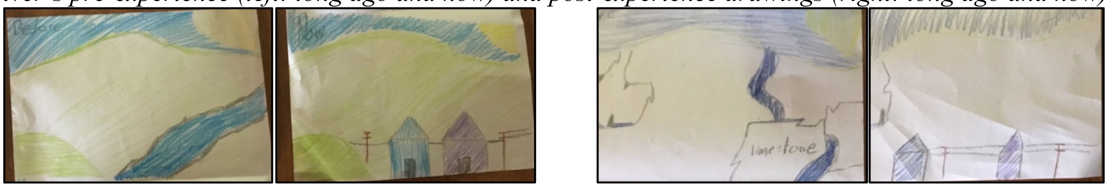
Screenshot of the Sandstone Boulders (left); Tanya and Oliver observing the rock



Tanya and Oliver actively engaged in a visual and tactile exploration of the rock's appearance and texture caused by erosion as they moved their fingers across its surface. Tanya used her body to guide Oliver where to touch the rock and look for the evidence of erosion. Additionally, Oliver compared the last limestone micro-site to the current sandstone micro-site as he compared the rocks that formed in different geological times.

Comparing Oliver's pre- and post-experience drawings (Figure 4) and responses in the interviews, Oliver adopted scientific vocabulary related to changes in the Appalachian area over millions of year (e.g., his language moving from terms such as "jagged" rocks and mountains to terms such as limestone, sandstone, ridges, and valleys). For example, in the pre-experience interview, he included a local mountain, a river, and some houses in his drawing (Figure 4, left), and when asked how caves were formed, he said tectonic plates formed caves; whereas, in the post-experience drawing (Figure 4, right), he noted a cave was eroded by water over millions of years. Oliver demonstrated a clearer understanding of what and how natural forces (i.e., water eroding rocks over a long time) shaped his community's present-day landforms.

Figure 4
Oliver's pre-experience (left: long ago and now) and post-experience drawings (right: long ago and now)



Case Study 2: Learning-on-the-move allowed families to integrate complex information about geological historic periods across the micro-sites of learning

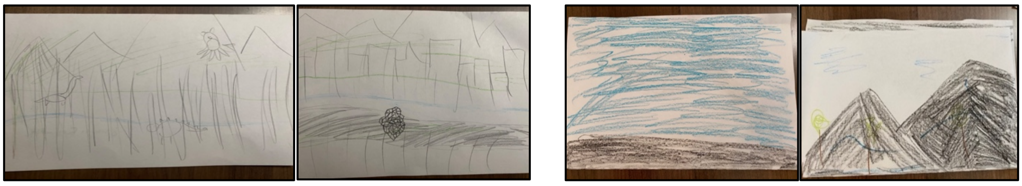
Our team designed for LOTM to allow for the geological time walk, anchored by MAR elements within the app. As they moved through the children's garden, families built knowledge about how Appalachia changed over geological time, as they connected information from different micro-sites of learning to see that Pennsylvania was under water millions of years ago. One example of this comes from one family, Jennifer (Mother), Amanda (Mother), Izzy (11-year-old girl), and Ethan (7-year-old boy):

Izzy: Look at this photo about ridges flowing. ((reads)) "Talk about what you learned." Let's talk about what we've learned. Sandstone. ((gestures toward Arched Rock Wall micro-site)) It's made of sandstone and limestone.
Amanda: Sandstone is made of sand and silica.
Izzy: Quartz and silica. [connects to Sandstone MAR micro-site content]
Amanda: Oh. Quartz and silica. Thank you. (…)
Jennifer: Ethan, do you remember what limestone is made from?
Ethan: Sand. ((touches arched rock wall))
Jennifer: Nope. Close. It has to do with the sea. [references Coral Sculpture micro-site content]
Izzy: Carbon — no
Ethan: Coral!
Izzy: What is coral made of?
Jennifer: It's sea creatures.
Amanda: Calcium. [connects to Limestone MAR micro-site content]

This case illustrates how the LOTM experience encouraged the family to connect information across the garden — synthesizing information from four MAR micro-sites together at the (human-created) Arched Wall, which simulated the strata of limestone, sandstone, and other rocks. Izzy, Amanda, Jennifer and Ethan discussed the connection of the sandstone and limestone in their community today (that makes up the visible ridges and valleys) to the prehistoric oceans (with coral) that covered Pennsylvania millions of years ago.

Similarly, Izzy's understanding of how Appalachia changed over geological time also shifted from the pre- to post-experience interview, illustrating her connecting multiple micro-sites and times from the immersive experience. Describing her pre-experience drawing (which both contained mountains, trees, and a river (Figure 5, left)), she said: "I would say that the land hasn't changed too much, except for the humanity that has come to, um, destroy everything in its path." Her post-experience drawings, however, show her understanding of how the land has changed over geological time as shown through multiple micro-sites in *Time Explorers*: "mountains from plates pushing the other, and trees, and rivers from erosion" (Figure 5, right). The difference in her descriptions and drawings of how Pennsylvania has changed over geological time demonstrates that she gained an understanding of how water, rock, and tectonic plates influenced Appalachia over millions of years.

Figure 5
Izzy's pre-experience (left: long ago and now) and post-experience drawings (right: long ago and now)



Case Study 3: Discussion prompts and photographic features of the MAR app encouraged talk about how geological history changed the community landscape

The discussion prompts and photo-taking activities in *Time Explorers* facilitated families' in-situ science observation. For instance, in response to the discussion prompt "*Look closer at limestone boulders and talk about what you see*," Helen (Mother), Noah (11-year-old boy), and Jesse (9-year-old boy) collaboratively observed the limestone rocks.

Jesse: ((kneels and touches the rocks)) I sort of see... Is that rust? (Figure 6a)
Noah: Yeah. It looks like some.
Jesse: It looks like rust or copper.
Helen: I think there's something growing, don't you think, Jesse? It just happens to be that color.
Noah: Yeah. It looks like this is probably what—maybe calcium? Something that definitely has hardened over time.

Later, Helen walked and pointed out another rock that had cracks on it (Figure 6b), which gathered the boys closer and led them to discuss the hypothesis of water and rock interaction in the past created the cracks in the present time:

Helen: Okay. ((walks to the right)) What do you think these things are? ((points at another rock)) (Figure 6c)
Noah: I think those were pools of water.
Helen: Are these fossils?
Noah: ((walks to the right side of Helen)) No, I think those are pools of water. Just like really like — grew.
Jesse: Yeah, because pools of water make cracks like that ((points at another rock and walks around the rock)). (Figure 6d)

Figure 6
Helen, Jesse, and Noah use the family discussion prompts embedded in the app to notice cracks in rocks to understand that water and rock, together shape how Appalachia has developed over millions of year.

(6a) **(6b)** **(6c)** **(6d)**

In the process of discussing the prompt, the family shared their observations of the limestone rocks on-the-move. Walking to different spots around the Limestone Boulders, they first shared their observations of interesting rock textures aloud then collaboratively built different hypotheses of how the cracks on the rocks might form over geological time by drawing upon each other's observation.

In addition to the discussion prompts, the photo-taking activities embedded in the app also supported families to apply the augmented information to their observation in-situ. For instance, while Jesse was taking photographs at the In-and-Out Creek at another micro-site, Noah walked around a simulated stream to find evidence that represented water eroding limestone rocks to create water gaps:

Noah: Come over here! There's something you got to see. Look, you can see how there — it's very eroded. ((Helen and Jesse walk to Noah))
Helen: Isn't that cool?
Noah: It's very eroded in that area. ((points to the rock))
Jesse: It looks like it has three layers. ((takes a photo))

The photograph-taking activity supported the family in noticing and observing rock features that matched what they learned about water gaps from the app earlier. Through taking photos, the family made collaborative observations. Though Noah was not holding the device to take photographs, he was actively participating in the learning process as he constantly moved around, looked for evidence, and shared his observations aloud with Jesse and Helen. This pattern was commonly seen across families with more than one child, where parents and siblings took turns taking photographs and helping each other locate interesting, picturesque spots.

Discussion

Theoretically, our work further conceptualizes the role of the LOTM social learning process in an outdoor learning environment. Prior work sought to understand naturalistic perspectives on LOTM with technology (Silvis et al., 2018; Taylor, 2017) and without (Ma, 2017; Marin, 2020). In our study, we designed the *Time Explorers* app with LOTM principles, so LOTM became a pedagogical tool used to advance the geological time narrative. By moving through eight micro-sites representing eight different geological times in a children's garden, families relied on a time travel narrative to support their temporal understandings of complex geosciences concepts. Both the families' talk in situ and the families' pre- and post-experience drawings (e.g., Figures 4 and 5) provide evidence of the LOTM experience allowing participants to understand how water-rock interactions shaped community landforms over millions of years.

The case study analyses illustrated how MAR can support family conversations that integrate complex hydrogeological concepts throughout the learning experiences. The prior research (e.g., Cervato & Frodeman, 2012) has shown that developing geosciences understanding can be challenging; however, families in our study nonetheless connected multiple MAR micro-sites (i.e., Jennifer, Amanda, Izzy, and Ethan) to build complex understandings of how water, sandstone, and limestone interacted to create their community's present landscape.

Given the importance of sensory observations in outdoor learning (Ballantyne & Packer, 2009; Beery & Jørgensen, 2018), we found evidence that using the MAR app encouraged sensory observation in the children's garden with the digital content supporting, not distracting, families' outdoor explorations (i.e., Tanya and Oliver). The app's prompts suggested that families compare and contrast textures of limestone and sandstone rocks and find and discuss the visual evidence of water gaps, patterns in rock strata, and erosion. All the families in the study engaged in tactile and visual sensory engagement during the observation of concepts related to Appalachian geological time in response to the *Time Explorers* prompts and activities.

Finally, our analyses elucidate how the MAR app's photo-taking activities and discussion prompts could be successful tools in an app designed for rural families' outdoor learning (e.g., Figure 2 and Noah, Jesse, and Helen). While photo-taking and discussion prompts have been used in informal spaces in prior work, our research adds to the utility of these tools while LOTM during outdoor education experiences and to support geosciences observations. Prior literature reviews (Eberbach & Crowley, 2009) found little evidence of people recording and referring to observational notes when engaging in out-of-school-time science. Here, the families used photographs to capture and conversations to reflect on their observations as they moved through a children's garden; these tools were easy to deploy on a MAR app and quickly taken up by families.

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