Intern. J. Comput.-Support. Collab. Learn (2023) 18:291–322
https://doi.org/10.1007/s11412-023-09399-9

Mobile augmented reality supporting families' immersive collaborative learning: Learning-on-the-move for place-based geoscience sense-making

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Received: 29 June 2022 / Accepted: 11 May 2023 / Published online: 26 July 2023

Abstract
We investigated how families experienced immersion as they collaboratively made sense of geologic time and geoscience processes during a place-based, learning-on-the-move (LOTM) experience mediated by a mobile augmented reality (MAR) app. Our team developed an MAR app, *Time Explorers*, that focused on how rock-water interactions shaped Appalachia over millions of years. Data were collected at the Children's Garden at the Arboretum at Penn State. Data sources were videos of app usage, point-of-view camera recordings with audio capturing family conversations, and interviews from 17 families (51 people). The analytical technique was interaction analysis, in which episodes of family sense-making were identified and developed into qualitative vignettes focused on how immersion did or did not support learning about geoscience and geologic time. We analyzed how design elements supported sensory, actional, narrative, and social immersion through photo-taking, discussion prompts, and augmented reality visualizations. Findings showed that sensory and social immersion supported sense-making conversations and observational inquiry, while narrative and actional immersion supported deep family engagement with the geoscience content. At many micro-sites of learning, families engaged in multiple immersive processes where conversations, observational inquiry, and deep engagement with the geoscience came together during LOTM. This analysis contributes to the CSCL literature on theory related to LOTM in outdoor informal settings, while also providing design conjectures in an immersive, family-centered, place-based LOTM framework.

Keywords Place-based education · Augmented reality · Informal learning · Geosciences education · Immersive learning · Computer-supported collaborative learning

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Introduction: The potential for collaborative extended reality technologies in outdoor informal environmental settings

Addressing environmental problems in communities (e.g., lack of fresh water, low water quality, sinkholes affecting development, and aftermath of mineral mining) requires people to develop complex geoscience understandings to create real-world solutions that integrate concepts across various geographic and geologic time scales. Yet understanding the scale of geologic time, the scope of land–water interactions, and related geoscience phenomena is difficult for learners (Cervato & Frodeman, 2012; McDonald et al., 2019), in part because such concepts are not easily seen or experienced directly. Additionally, successful environmental education entails collaborative learning that is "…more likely to occur when education programs involve the wider community—and across generations" (Gambino et al., 2009, p. 84).

Recent computer-supported collaborative learning (CSCL) research has begun to explore extended reality (XR), a broad category of learning technologies that includes virtual reality (VR), mobile augmented reality (MAR), and setting-bound augmented reality (AR) for science learning in informal settings. XR can be employed as a learning tool in CSCL in different ways depending on (a) the technology (headset, table-top, or mobile device), (b) the place (digital only, digital with an imagined place, or digital in an actual setting), and (c) the mode in which the learners collaborate socially (engage with computer-generated agents, peers, or teachers online asynchronously, and/or family, peers, or teachers in real time). XR has been effectively used as a tool to make hard-to-see scientific concepts visible (Yoon & Wang, 2014; Yun et al., 2022); increase science learning outcomes, motivation, and engagement (Goff et al., 2018); and decrease science misconceptions (Kennedy et al., 2021). For instance, Kennedy et al. (2021) developed an AR exhibit at La Brea Tar Pits Museum to help adult visitors visualize Ice Age animals virtually onsite as they would have appeared during prehistoric time. They found that, after a 6-min AR experience, participants had fewer misconceptions and a higher reported interest in science. Likewise, Yoon et al. (2012), reported that students increased their conceptual knowledge of electrical conduction and circuits after an AR augmentation of a museum exhibit that projected the flow of electrons when an electrical circuit was completed.

Building on the success of XR in museums along with advances in the portability, accessibility, and location awareness of mobile devices, it is now possible to develop CSCL environments to support environmental sciences learning outdoors. Outdoor locations provide rich resources and opportunities for learning about and engaging the natural world within communities (Gambino et al., 2009). MAR uses mobile devices to deliver digital learning resources that are triggered by Global Positioning System (GPS) location and by scanning an object or marker such as a quick response (QR) code (Ryokai & Agogino, 2013). MAR blends virtual elements such as digital content, videos, or graphics with the physical environment. This blending of digital elements with the physical space enables designers to overlay complex educational content onto specific locations to direct learners' attention to important features that they might not notice (Dunleavy & Dede, 2014) and to scaffold collaborative sense-making through prompts, questions, or other supports (Zimmerman & Land, 2022). MAR has been increasingly studied in environmental learning centers such as botanical gardens (Huang et al., 2016), woodlands (Zimmerman et al., 2015; Rogers et al., 2004), and ponds and lakes (Georgiou & Kyza, 2021) as a learning tool to reveal complex scientific concepts that would be difficult or impossible to support through interpretive signage alone. Many outdoor environmental learning centers use minimal interpretive signage to preserve the natural space and the aesthetics of nature; also, signs do not allow for interactive videos, animations, photo-taking, or other engaging MAR features.

Even with the promise of MAR to support outdoor CSCL related to the environmental sciences, several gaps in the literature motivated the current study. First, although MAR is increasingly being used to support outdoor STEM learning, students on school field trips or summer camps are typically the learners of focus (Land & Zimmerman, 2015; Georgiou & Kyza, 2021; Kawas et al., 2019; Rogers et al., 2004). According to a 2019 meta-analysis by Garzón et al. of AR studies in educational contexts, the most commonly studied learners are younger children (primary/elementary school) and college students. But families are the primary users of informal learning institutions, including outdoor learning spaces (Yun et al., 2022), yet they are understudied. In response, we explore the role of MAR to support intergenerational family audiences to learn geoscience in an out-of-school, outdoor activity.

Second, other studies have implemented XR to augment exhibits within museum settings (Beheshti et al., 2017; Goff et al., 2018; Kennedy et al., 2021; Yoon et al., 2012; Yun et al., 2022), but they typically focus on a short, discrete visualization of one concept or exhibit, with less focus on sense-making that connects multiple concepts, histories, and exhibits over time. CSCL needs empirical studies on the role of connecting digital content across outdoor spaces while people are moving because visiting an environmental learning center often involves traveling on paths or greenways with a mobile phone. Hence, gaining insights into how to support collaboration in such contexts is warranted. We used MAR to support family groups to make conceptual connections and have continuous engagement across multiple objects, specimens, and art installations as they moved throughout an outdoor community space.

Third, some prior studies have used MAR in outdoor settings to superimpose educational games into a space to solve a science-related mystery or fictional problem (Georgiou & Kyza, 2021; Squire & Jan, 2007). The focus of these studies is often on building scientific explanations/solutions for a fictional problem versus deeply observing, interacting with, and learning about one's environmental surroundings. As in these prior studies, our MAR app also employs a driving, fictional narrative to guide the MAR immersive learning experience (i.e., time travel); however, we extend prior approaches by customizing science content, AR visualizations, and conversational prompts to focus families' attention on sensory experiences specific to the environmental landscape and history of the community.

Methodologically, our analyses add to the literature by highlighting how interactions among all elements of the learning experience—designed, immersive qualities of an MAR app, collaborative sense-making talk, movements of the family, and physical elements across the space—contributed to family learning. Specifically, our MAR app design focused on developing content to support eight linked microsites (Sharples & Pea, 2014). A microsite is the intersection of the groups' interactions, the digital MAR content, and the physical setting. For our purposes, microsites included our MAR resources and design intentions, the outdoor center's outdoor exhibits, and the families' emergent interactions based on each family's unique sociocultural history. The microsites concept allows for the design of sociotechnical interactions in ways that support a culturally inclusive approach to the learning of geoscience content during an immersive CSCL experience.

Conceptual framework: Learning-on-the-move (LOTM) with place-based MAR

Within our research and development efforts, we consider place in a sociocultural–historic manner—as more than a geographic location; we adopt the perspective of Lim and Barton (2006), where place includes overlapping geographical, temporal, ecological, social, political, and cultural elements. Our place-based geoscience perspective draws from Semken (2005), who asserted the importance of focusing on learners' meanings of place and developing scientifically sound and culturally relevant interventions, most often via on-site (versus just classroom) engagement. Relatedly, Eijck and Roth (2010) argued that educators must reflect a place's multiple meanings, including those held by nondominant cultural groups. Related to this research, Marin and Bang (2018) posited that families learn about a place by moving through its spaces together because "walking, reading, and storying land cultivates learning about the natural world and coming to know one's place in the world" (p. 89).

Geologic time scale is a foundational geoscience concept for understanding place. Geologic time "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). Geologic time tells the story of how a community's ridges, valleys, rivers, and lakes came to be after millions of years of movements of tectonic plates, as well as processes of erosion and deposition as water and ice interacted with rocks and minerals. Although geoscientists determine earth's geologic time by observations and analyses of rock strata, mineral composition, and the fossils that the strata contain, novices too can engage in a developmentally appropriate version of observing rock strata by connecting rock type and location to key events in the past (e.g., noticing limestone rock revealing high levels of calcium in the past, the location of layers of sedimentary or igneous rock, and places where tectonic movements have disrupted rock strata).

Although noticing evidence of geologic time scale is possible for novices, Cervato and Frodeman (2012) asserted that learning about geologic time is difficult. Novices can mistake the timing of key geological events (e.g., formation of mountains and landform movements), confuse the timing and distance between geological periods, and have a limited understanding of the rate of erosion, deposition, and landform movements. Geoscience educational researchers (e.g., Orion & Ault, 2013; Resnick et al., 2017; Tretter et al., 2006) have investigated pedagogical techniques such as analogies, moving through a scaled version of time or distance, or time-lapsed videos that help address learning struggles when faced with these challenging concepts. To address these learning challenges, our research and development efforts led to the designing of an MAR app for collaborative intergenerational learning that brings together two key concepts to design for and analyze families' sense-making about geologic time scale: (a) LOTM as a social learning process, supporting families as they move in groups across a community-oriented space and (b) immersion (i.e., sensory, actional, narrative, social, and emancipatory) as a pedagogical strategy to reveal to families evidence of the past in the rocks through observation of actual and simulated cave and rock strata on-site.

Learning-on-the-move: Social learning incorporating movements in and about place

LOTM describes a social learning process in which people collaboratively make sense of new information as they move their bodies within and through space (Zimmerman & Land, 2022; Marin, 2020; Silvis et al., 2018; Taylor, 2017). LOTM includes small and large motions, such as gesturing, pointing, reshaping one's posture, walking, wheel-chairing, biking, hiking, climbing, dancing, and engaging in other playful movements. Movements, such as gestures, are a supportive sense-making approach in science and mathematics education (e.g., Alibali & Nathan, 2012), including movements coupled with technology use (Kang et al., 2021). For technologically supported LOTM, researchers use MAR to tie disciplinary information or game-like narratives to place, so people's movements through spaces embody the app's storyline, such as *Environmental Detectives* (Klopfer & Squire, 2008) and *Mysterious Disease* (Georgiou & Kyza, 2021). When analyzing people's 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 settings. 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 children's garden. Drawing from Ma (2017), who considered large-scale "multiparty, whole-body interactions" as critical in learning geometry, we designed learning experiences for families whereby moving their bodies—leveraging multiple body–place interactions—could be used to make sense of geologic time in a children's garden.

Finally, LOTM is critical to understanding people's social learning interactions in outdoor spaces. Beery and Jørgensen (2018) found that, when children play outdoors, their play includes body movement and sensory engagement. We align our research and design efforts with the claim of Marin (2020) that "walking and lands/waters have always been and continue to be central to human learning, development, and activity (p. 282)." Moving through community spaces to engage with landforms and water bodies encourages social interactions between those who are walking; for instance, the learning practices of questioning, directing, and narrating were critical social interactions used by families (Marin & Bang, 2018) as families engaged in sense-making of the natural world. We build on our prior definition of sense-making in informal science settings (Zimmerman et al., 2010) where families' talk connects their existing knowledge, prior experiences, and shared memories to new phenomena, and as such, our designs left space for families' movement and sense-making conversations to allow for social learning to occur.

Given the theoretical promise of LOTM and the technical affordances of XR technologies, the CSCL field now needs effective, empirically based guidelines and frameworks for supporting MAR in social groups in the outdoors. Our work seeks to provide insights into the utility of one empirically based design framework for MAR (Enyedy & Yoon, 2021), discussed below: immersive, family-centered, place-based LOTM.

Design framework: Immersive, family-centered, place-based LOTM

One critical element of XR technologies is how they foster immersion—defined as the sense of how holistic and realistic an experience is—for learners (Dede, 2009). Immersion (Enyedy & Yoon, 2021) can be supported in an MAR app to create an experience in which learners either imagine they are in a different or hybrid setting or become deeply engaged in exploration or role-play. Enyedy and Yoon have conceptualized a five-part framework to differentiate the types of immersion in XR (2021): sensory, actional, narrative, social, and emancipatory (SANSE). These five processes are not exclusive but work together to create a sense of immersion in an alternative or a hybrid digital world for learners.

Sensory immersion is the role of digital graphics and interactions that make a person feel as if they were present in the actual setting represented by the form of XR (Enyedy & Yoon, 2021). In place-based MAR, sensory immersion can be fostered through prompts and text that encourage tactile and visual observations within the outdoor learning setting. In environmental education, sensory engagement is essential to the learning experiences (Ballantyne & Packer, 2009). Our earlier work (McClain & Zimmerman, 2016) defined sensory engagement as gestures and movements that foster visual, auditory, and tactile observations; create joint attention (i.e., pointing); or encourage sense-making discussions. Through sensory immersion, learners engage in visual and tactile noticing to support scientific observation (Eberbach & Crowley, 2009). Mogk and Goodwin (2012) argued 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).

Actional immersion includes the actions, movements, and gestures that are hindered or allowed within an XR environment (Enyedy & Yoon, 2021). In MAR, this includes within-app activities such as photo-taking and real-world activities such as using a GPS map for wayfinding to the next location. Designers can employ immediate and long-term actional immersion processes, referred to as tactical and strategic activities, respectively, by Enyedy and Yoon (2021).

Dede (2009) defined narrative immersion as the design of the XR environment to create an imaginative or story-like experience. Narrative immersion processes have multiple elements in XR as in other forms of storytelling, including a plot with temporal and spatial/place (including cultural and historical) elements, and characters or role-taking (Enyedy & Yoon, 2021). Narrative immersion is an important pedagogical element of the design, as narratives are effective pedagogical supports in AR (Georgiou & Kyza, 2021) and in mediating people's understanding of science-related topics (Dahlstrom, 2014). We add to Dede's definition with the inclusion of a learner-driven narrative immersion in which designers allow space for families' own storying of landforms and water bodies (Marin & Bang, 2018) by adding discussion prompts or learner-created digital artifacts.

In many forms of XR, social immersion includes interactions with agents or nonplayer characters, but in place-based AR, social immersions include face-to-face interactions with peers engaged in the learning experience (Enyedy & Yoon, 2021). Enyedy and Yoon asserted that social immersion can also include aspects of an XR experience that allow learners to feel part of a community or group. Informal learning research (e.g., Zimmerman et al., 2010; Crowley & Jacobs, 2002) asserts that, when learning together, parents guide youths' participation by generating interest and building collaborative knowledge. In informal settings, children learn science more deeply when an adult assists (Fender & Crowley, 2007); however, parents may miss opportunities to support children fully in scientific talk and thinking (Gleason & Schauble, 1999), so social immersion prompts can serve as discussion guides for the family. CSCL research on technologies used in informal and everyday spaces (e.g., Zimmerman & Land, 2022; Ha et al., 2021; Roberts & Lyons, 2017; Shapiro et al., 2017; Silvis et al., 2018) has reinforced the significance of social interaction and talk, especially when combined with LOTM. Supporting parent–child conversations during LOTM outdoors is particularly important for encouraging collaborative sense-making when there is only one mobile device that is being shared by the family (Yun et al., 2022).

Finally, the last process in Enyedy and Yoon's (2021) framework is emancipatory immersion, in which aspects of the XR environment support learners in taking action or engaging in thinking that supports community organizing, social justice, stewardship, and connections to others. Within our topic of environmental education, emancipatory research has included ethnographic approaches related to understanding the impacts of the local environment, social justice (e.g., Davis & Schaeffer, 2019; Tzou et al., 2010), and the effects of generational differences in environmental understanding on school-based learning (Zimmerman & Weible, 2017). With emancipatory immersion, designers can align community concerns with environmental education related to local land, water, and habitats concepts.

Research question

We designed this study to bring together the technological affordances of MAR with the social learning theory LOTM and the design framework of immersion. As a result, in this paper, we ask:

- How do families experience immersion as they collaboratively make sense of geologic time scale and geoscience processes during a place-based LOTM experience mediated by an MAR app?

Method: Qualitative case study as iteration one of a design-based research project

Outdoor setting and research partners

The study location was the Children's Garden at the Arboretum at Penn State, which is associated with a large land-grant university in the Mid-Atlantic region of the USA. The Arboretum is an expansive outdoor informal learning institution consisting of a variety of gardens and groves, including living plant and tree collections, display and ornamental gardens, a pollinator and bird garden, pond and fountain features, sculptures, and more than 100 acres of adjacent natural lands comprised of wetlands, prairie restoration, wildflower trails, meadows, and an old-growth remnant forest. The Arboretum also contains a Children's Garden, which is a play space designed around exploring nature, vegetable plantings, and exhibits and sculptures representing animals, plants, indigenous cultures, and the region's geological history. The Children's Garden spans several exhibits, including a model cave, various sculptures, simulated rock walls, and natural limestone and sandstone boulders—all of which represent or evoke aspects of the region's geological history.

Our project was driven by a 12-year partnership with the Arboretum that encompasses annual volunteering for field trips, serving on advisory boards and search committees, and holding on-site educational programming for our mobile learning research. We meet annually with the Arboretum's director, plant curator, director of development, and educators to ensure our goals are aligned with the organization's mission, values, and upcoming initiatives. For this analysis, the educational staff of the Arboretum provided additional regular feedback and reviewed beta versions of our app. Their feedback typically focused on providing insights into visitors' preferences and experiences, recommending optimum data collection times and locations, and raising the practical and logistical considerations of employing an app in their outdoor space.

Participants

Our study focused on 17 families ($N=51$) visiting the Children's Garden at the Arboretum at Penn State. For recruiting, we worked with various community partners (e.g., multiple rural libraries, a nature center, a science museum, and the Arboretum hosting our study) to advertise the research study via their websites, social media, listservs, bulletin boards, and bookmark shelves. To participate in the study, all family members had to consent (for adults) or assent (for children) to being video-recorded; however, a family could opt out of sharing their video at conferences or in publications. All images shown in this article had written permission to share identifiable images. Participating families required Internet access to complete online consent and participate in our Zoom interviews due to COVID-19 social distancing protocols.

Participants were recruited from two separate data collections. In Data Collection 1, 7 families living in two rural counties participated (8 adults, 12 youths). Most families had one parent or legal guardian that attended the program, with one family having two parents/legal guardians present. Five families had two children participating, and two had one child participating. Guardians self-reported their families' racial affiliations as white (100%); two children were also guardian-reported as other (10%). Children (female: 25%, male: 75%, nonbinary: 0%) were primarily 5–12 years old (ages 0–4 years: 8%; ages 5–8 years: 50%, ages 9–12 years: 42%, ages 13 + years: 0%). Two guardians were scientists; two were administrative staff. Other self-reported occupations of the guardians were writer, farmer, and educator. One family homeschooled their children. All families had visited the Arboretum before.

In Data Collection 2, which occurred 4 months after Data Collection 1, 10 families living in one rural county participated in the research (15 adults, 16 youths). Of the 10 families, five (50%) attended with one parent/legal guardian, and five (50%) had two parents/legal guardians attending. Four families had one child that participated, while six families had two children that participated. 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%, nonbinary: 0%) were primarily 5–12 years old, with a higher percentage of children 8 years and younger participating in this iteration than in iteration 1 (ages 0–4 years: 6%; ages 5–8 years: 69%; ages 9–12 years: 25%; ages 13 + years: 0%). Four guardians were educators (e.g., teachers, instructors, or professors); three were unemployed; and others' self-reported occupations included researcher, program specialist, homemaker, human resources staff, illustrator, chief financial officer (CFO), self-employed, and military. Two families homeschooled their children.

Our participant recruitment strategies had strengths and weaknesses. We recruited rural families from local community institutions. This recruitment technique allowed us to reach our target audience of families likely to attend a rural outdoor community space; however, we may have over-recruited families who were already interested in science or environmental topics. We provided all on-site technology (i.e., iPads to borrow) to be equitable to participants, but we acknowledge that we may have only reached families with ample technological resources, such as high-speed Internet, due to ongoing stay-at-home restrictions related to the COVID-19 pandemic.

Our recruitment techniques also oversampled families who identified themselves as white. The parents/legal guardians who attended the program identified primarily as the children's mothers; only four out of 23 parents identified as fathers. Additionally, our data collection protocols excluded adults who were not the child's parent or legal guardian. We attribute this oversampling of white families and mothers to pandemic issues affecting multiple communities in the USA—childcare requirements with school closures, work-at-home stresses, and financial challenges that were not equally distributed across racial groups or economic statuses. Diversity in our study population came in other forms (self-reported by families), including socioeconomic status (SES; using job types as a proxy for SES) and attending homeschool versus public school.

Time Explorers MAR app features and technology

The *Time Explorers* MAR experience was approximately 30–40 min as families completed a narrative time-travel journey. After initial welcome screens, the families were introduced to the narrative story of the app—time travel—through the geological history of Appalachia in the Children's Garden. The app featured an animated spinning time spiral (Fig. 1, left), which oriented the family to the geologic period they were in and the time period that they were moving toward. The app then displayed an illustrated map of the Children's Garden with the family's location identified by a blue dot and an arrow surrounding the dot to show the direction they were headed (Fig. 1, right). The next location was identified by a white circle and a close-up image of the setting. A white text box appeared at the bottom of the map with instructions. Once the family arrived at the correct location, the screen changed with new science content and AR materials that were triggered by proximity to the microsite's GPS coordinates.

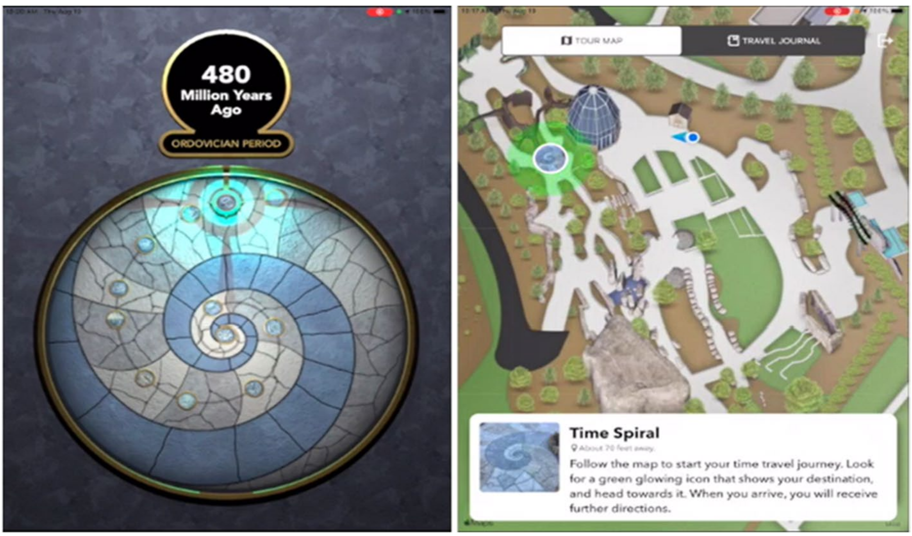


Fig. 1 The time spiral animation was used to orient families to the geologic time period (left), and the GPS map (right) aided wayfinding

Eight microsites related to geological time and other app features

Time Explorers was divided into eight microsites organized by geologic time (starting at prehistory). Guided by the GPS map (Fig. 1), learners moved forward in time to understand how vital landforms of the area were formed in Appalachia (as shown in Table 1). Families walked throughout the garden, driven by the time-travel narrative, stopping to learn more about geologic time at the following predetermined locations (in this order): (a) Time Spiral Sculpture (Ordovician Period), (b) Coral Sculpture, (c) Limestone Boulders, (d) Sandstone Boulders, (e) Arched Rock Wall Model, (f) In-and-Out Creek water feature, (g) Model Cave, and (h) Spring Basin water feature.

Study design

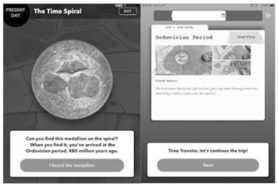
Our overarching research goals fall within the vein of design-based research (DBR; Sandoval & Bell, 2004) to simultaneously (a) advance theory related to LOTM and AR immersion and (b) enrich educational practice related to the design of outdoor informal learning environments. This paper uses a qualitative case study (Yin, 2014) to report on the first iteration of our DBR study. Our case study is based on two separate data collections that utilized similar data collection protocols and versions of the MAR app. For Data Collection 2, the MAR elements were the same as in Data Collection 1; however, we added an AR filter family selfie at the end of the experience, a back button to improve navigation, and text edits for clarity as well as fine-tuned the GPS coordinates for the Model Cave location. We use an interpretive, qualitative method of data collection and analysis to foreground the meanings and experiences that family learners had with our design. We focus our CSCL analytical approach on the family group as a social unit of analysis (Stahl & Hakkarainen, 2021), highlighting how the family engaged in meaning-making as a group during their real-time interactions with the MAR app, movements within place, and their conversations with each other.

Data collection

Due to COVID-19, our dataset was collected with a social distancing protocol. The primary data used in this article included families' iPad screen recordings and GoPro videos that captured their talk and interactions in the Children's Garden. These data were selected because they captured the families' experiences using the MAR app. Due to social distancing protocols, each family met one researcher on-site, one at a time. The researchers provided each family with a bag containing sanitized equipment. Families then used a laminated job aid to turn on the screen recording feature of a borrowed iPad (with the *Time Explorers* app running) and to turn on a hat-mounted GoPro video camera that recorded their experience in the first-person view. (The screen recording and GoPro both captured families' audio to have redundant data sources.) The socially distant data collection strategy was imperfect—one family's GoPro video and four families' screen recordings (out of the 17 total families) were not fully captured due to technical difficulties. The screen recordings and GoPro videos from each family were merged into one side-by-side file for data analysis. Either the screen recording or the GoPro audio was professionally transcribed (depending on quality). These transcripts were then checked by two researchers for accuracy to add relevant gestures and to note

Table 1 The eight microsites for the *Time Explorers* MAR learning experience and the ninth celebratory selfie activity

<table>
<tr><th>Physical Location in Children's Garden</th><th>Narrative</th><th>MAR Elements</th></tr>
<tr><td>1. Time Spiral Sculpture of geologic time

Families walked on a sculpture starting from the present day to the Ordovician period, 480 million years ago.</td>
<td>Become a Time Explorer as you walk through geologic time and explore how the region's prehistoric geology created today's ridges and valleys.</td>
<td>• Digital resources (text, graphics, and an AR animation of a time spiral time machine spinning back in time) helped families interpret the geologic time spiral representation and movement from prehistory to today.
• Sensory prompt: "Can you find this medallion on the spiral? When you find it, you've arrived at the Ordovician period, 480 million years ago."
• Sense-making activity: Families took photos of the Ordovician period medallion for their time travel journal, integrating the MAR geological time narrative and their visit to the Children's Garden.

</td></tr>
<tr><td>2. Coral Sculpture

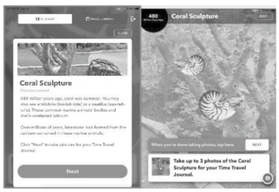
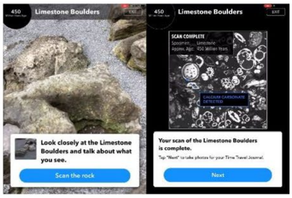
A large sculpture of coral representing when the region was underwater. Over time, calcium from marine animals created limestone rock.</td>
<td>See what the region looked like during the Ordovician period when a shallow ocean covered it, and it was located near the equator.</td>
<td>• Digital resources explained how limestone rock formed from calcium found in the bodies of marine animals.
• A blue-tinted AR filter with animation showed an underwater scene with floating nautili. Families' photos include a blue tint to evoke an underwater scene.
• Sense-making activity: Families took photos of the coral sculpture to connect the representation with scientific content about ancient marine animals rich in calcium.

</td></tr>
</table>

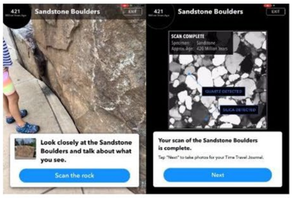
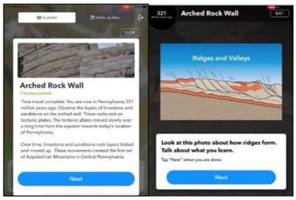
Table 1 (continued)

3. Limestone Boulders  Rock garden consisting of limestone boulders typical of the region.	Travel forward 30 million years in time.	• Digital resources showed that a) limestone rock is formed from calcium from sea animals' exoskeletons, and b) limestone rock erodes easily. • AR animation showed a virtual microscopic scan of the boulders' mineral composition (calcium carbonate). • Sensory prompt: "Look closely at the Limestone Boulders and talk about what you see" • Sense-making activity: Families took photos of the limestone boulders to deeply observe limestone and rock erosion. 
4. Sandstone Boulders  Sandstone rock garden	Travel forward in time 29 million years to the Silurian period, when sandstone was deposited on the ocean floor over limestone.	• Digital resources explained that sandstone is made of quartz and silica, is porous, and does not erode easily. • AR animation showed a virtual microscopic scan of the sandstone's mineral composition (quartz, silica). • Sensory prompt: "Look closely at the Sandstone Boulders and talk about what you see" • Sense-making activity: Families took photos of sandstone boulders to deeply observe sandstone and consider how water can flow through certain rock layers.

if a family member was reading from the app, using the merged screen-recording/GoPro videos, as necessary.

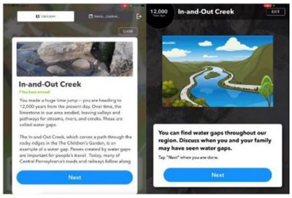
Additional data sources were used to triangulate the interactions captured on the video recordings, including 17 pre- and post-experience interviews via Zoom and 17 online demographic survey responses. In Data Collection 1, the pre-experience interview included questions on how ridges, valleys, and caves formed and if the family had prior experience with caves. The post-experience interviews included (a) the same questions about how

Table 1 (continued)

		
5. Arched Rock Wall  A rock wall with layers of limestone and sandstone rock folded and bent by the movement of tectonic plates.	Travel forward in time to 321 million years ago.	• Digital resources (text, graphics) showed how layers of sandstone and limestone rock were deposited and moved by tectonic plates, forming the first set of Appalachian Mountains. • Geoscience graphical representation prompt: "Look at this photo about how ridges form. Talk about what you learn." • Sense-making activity: Families took photos of the rock wall to deeply observe rock strata and compare to a geoscience representation related to tectonic plate movement. 

ridges, valleys, and caves formed, (b) a drawing task that asked the children to draw how ridges, valleys, and caves formed, and (c) the family's overall impressions of the app. For Data Collection 2, we refined our data collection protocol slightly to better understand what children knew about how caves, ridges, and valleys are formed in their community both before and after the experience: The pre-experience interview included (a) a drawing task that asked the children to draw a picture of how ridges, valleys, and caves formed in the local landscape, (b) questions on how caves are formed, and (c) questions on how water shaped the landscape over time. Follow-up probing questions were asked about the drawing task and cave formation questions. The post-experience interview asked the same questions and used the same drawing task, but we added a question about whether families had seen any of the landforms in the Arboretum/app before. For Data Collections 1 and 2, all children participated in the drawing task, with families able to assist or discuss while the children drew. To organize the drawing task interview, questions were directed to the oldest child first, then other children if present, and then the parents.

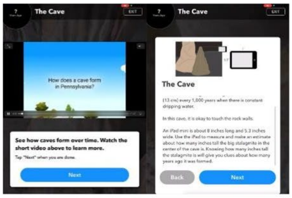
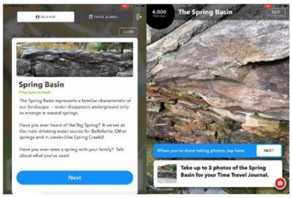
Table 1 (continued)

6. In-and-Out Creek  A water feature (a water gap) runs between the rocky ridges of the Children's Garden.	Time travel to 12,000 years before the present day (Quaternary period), when limestone rock was eroded by water, forming valleys and water gaps.	• Digital resources (text, illustrations) showed what water gaps look like in the region and explained how they formed from the erosion of limestone rock by water. • Family prompt: "Discuss when you and your family may have seen water gaps." • Sense-making activity: Families took photos of a simulated creek to consider how limestone erosion forms water gaps. 
7. Model Cave  A large model cave with stalactites, stalagmites, columns, dripping water, and bat sculptures.	Time machine sensors stop working, and the geologic time period is unknown. Families are asked to help determine the time period.	• Digital resources (text, illustrations) showed that caves form when water mixes with carbon dioxide, which dissolves limestone, while the sandstone rock remains. • Sensory prompt: "Look around. Can you see and hear dripping water?" • 2-D animation showed how caves formed over millions of years. • Family activity: Estimate the age of a stalagmite by measuring its height to find clues about the time period and fix the time machine. • Sense-making activity: Families took photos of a simulated cave to document the processes of cave formation from limestone.

Data analysis

To analyze how families experienced immersion as they collaboratively made sense of geologic time scale and geoscience processes during their LOTM *Time Explorers* experience, we conducted an interpretive, qualitative analysis of the screen recordings (13 whole and 2 partial) and GoPro videos (16 full). The analyses for this paper were all conducted at the

Table 1 (continued)

		
8. Spring Basin  A model spring, showing underground water formation prevalent in the region that emerges as freshwater springs.	Time travel to 4,000 years before the present day.	• Digital resources (text, photos) explained how limestone rock erosion can create streams that disappear underground and emerge on the surface as a spring. • Family prompt: "Have you ever seen a spring with your family? Talk about what you've seen." • Sense-making activity: Families took photos of a simulated spring to understand that water in the local area is often found underground. 
9. Family Celebratory Selfie 	The time travel journey ends in the present day.	• At the end of the time travel journey, families see an AR filter with elements of their time travel journey. • Celebratory activity: Families took a selfie photo to document their work as time explorers.

unit of analysis of the family. For our study, we defined a family unit as at least one parent/guardian with at least one child aged 5–12 years.

To conduct our initial interaction analysis (Jordan & Henderson, 1995), the authors held four initial co-viewing sessions with the broader research team to watch the merged screen recording and GoPro files. Based on the interaction analysis session notes, we developed short narrative case studies for all 16 families to illustrate how the MAR app's immersive characteristics influenced families' learning about geologic time scale. To further analyze the focal cases, a line-by-line analysis of the transcripts occurred, which highlighted how our MAR app immersion elements were connected to families' sensory engagement (verbal or tactile), verbally stated observations of geoscience phenomena, and/or explanations of geological history at each microsite. To understand the families' learning outcomes, the drawing tasks from each family were analyzed for evidence of learning about water–rock interactions.

After the initial analysis described above, the team set about a second iteration of analysis, which is presented in this paper. We re-read the computer-supported collaborative learning literature related to AR and LOTM based on curiosities about the immersive aspect of the learners' experience. The team then took a deeper dive into the immersive qualities of the experience. Full narrative analytical accounts were created for each family (an overview of the full experience with *Time Explorers*). After meeting to collaboratively review the full experience of each family, one episode was selected to create a vignette (i.e., an episode of family engagement at one microsite); each vignette was based on families' engagement with the five design conjectures, as shown in Table 2.

The authors next held four additional interactional analysis sessions to review vignettes (from each of the 16 families' video files), using the definitions of immersion in Table 2. In these sessions, we took notes on how the *Time Explorers* MAR immersive elements influenced families' talk, movements, interaction, and learning processes, and noted when families engaged in talk, interaction, and learning processes without the help of our MAR app. We crafted descriptions at these meetings focused first on the intersection of immersion, LOTM processes, and interactions with the MAR elements. We then developed vignettes to elucidate how the immersive qualities of an MAR app influenced families' understandings of geologic time scale and geoscience processes as they participated in the informal, LOTM experience in the Children's Garden.

From the 16 vignettes identified, we strategically sampled 4 families' vignettes—1 each that included sensory, actional, narrative, and social immersion processes (Enyedy & Yoon, 2021); we found no substantial example of emancipatory immersion from the data. We then identified one family that engaged in immersive processes very intensely; we consider this to be an ideal use case family. This fifth vignette was developed for this family to illustrate how multiple immersive processes could be manifest at one microsite location.

Finally, to prepare these vignettes for print publication (as opposed to interactive video), we adopted a comic strip format (McCloud, 2006) to display frames of the video with families' movements highlighted by lines and arrows and families' talk represented within bubbles. Recent work in the learning sciences has used comic-style imaging to convey how sociocultural practices shape learning in ways that entail complex interactions, energy, rhythm, emotions, and movement—for instance, community social movements (Curnow & Vea, 2021), civic engagement (Hollett & Ehret, 2017; Vea, 2021), and embodied, ensemble learning (Hollett et al., 2022). Comic representation in outdoor CSCL has shown joint attention through shared gaze and pointing (Zimmerman et al., 2019). We adopted the comic norm, common in the USA, to read the comic in the shape of a "Z," meaning the comics were designed to be read from top left to top right and then down to the bottom left to bottom right. To help our readers understand the order of utterances in the families' conversations, we numbered the text bubbles. To confirm the analyses, we presented findings and final vignettes to our broader team, getting feedback from colleagues to advance our thinking and refine our findings.

Table 2 MAR design conjectures for immersive, family-centered, place-based LOTM

Immersive category	Design conjectures	Time Explorers examples
Sensory	Learners engage in multimodal knowledge construction based on visual, auditory, and tactile experiences that enhance the sensation of being in a different place or time and visualize the unseen aspects of their community	• Prompts directed families' tactile and visual observations of specimens on-site • Prompts encouraged families to feel the textures and observe the appearance of sandstone and limestone rock • AR animations that visualized aspects of a place not normally visible (e.g., how caves form over millions of years and movement of tectonic plates)
Actional	Learners are directed to take family-centered actions, movements, and gestures to integrate concepts, construct understandings of scale, channel observations to key scientific phenomena, and unfold the story through wayfinding	• Participants captured photographic evidence of land–water interactions for the time-travel journal • Families used GPS for wayfinding to a specific location where learning resources were deployed • Short-term tactical actional immersion included walking the time spiral and measuring a stalagmite • Long-term, strategic actional immersion via prompts to make connections across various microsites
Narrative	Learners use AR filters and experience digital storytelling to (a) imagine that they are in a new place or time in their community, (b) make emotional connections to place and foster enjoyment of the experience, and (c) take on a new role to better understand their community	• Story elements invited families into the role of time travelers • MAR animations and filters simulated time travel (e.g., time machine animation) or a different geologic time period (e.g., AR filter with animated marine creatures creating the appearance of the region being underwater)
Social	Learners interact in family groups to have discussions and engage in collaborative place-based activities that support (a) sense-making focused on scientific phenomena and (b) personalization focused on shared experiences and funds of knowledge as relevant sense-making resources	• The place-based MAR app provided discussion prompts at specific locations to guide families to jointly engage in observations and sense-making conversations • Prompts supported families on how to talk about science together or how to build knowledge collaboratively • Prompts asked families to share aloud their prior experiences in their community related to water, rocks, and landforms
Emancipatory	Learners engage in experiences that support actions and ideas aligned with community organizing, social justice, stewardship, anti-racism, environmental justice, and connections to others' perspectives	• The text was grounded in the land, water, and habitats of a set of nearby rural communities—a population that is often underserved by informal learning institutions • Underground water in this community is key to understanding water quality and safety in this area

To enhance our data analyses' trustworthiness, the team conducted iterative data co-viewing sessions, shared notes, and double-checked transcripts. We also triangulated merged video data with families' pre- and post-experience interviews to compare our interpretation of families' experiences with their reflections and interpretations of working with *Time Explorers*. As the vignettes were developed, the first author re-read the full dataset and included evidence from other families that was both confirming and disconfirming of the LOTM process to represent a fuller picture of the families' immersive experiences. We shared our findings with people outside our research team at various points throughout our process to continue refining our approach and communicating our perspectives.

Data and findings

Our findings focus on how the immersive qualities of the *Time Explorers* MAR app influenced families' understandings of geologic time and geoscience processes as they participated in an informal, LOTM experience in the Children's Garden. Findings showed that sensory and social immersion supported sense-making conversations and observational inquiry, while narrative and actional immersion supported deep family engagement with the geoscience content. At many microsites, families engaged in multiple immersive processes where conversations, observational inquiry, and deep engagement with the geoscience content came together during LOTM related to land–water interactions.

Overall, the families who engaged with *Time Explorers* successfully navigated the app and its time-travel metaphor to move their family through the Children's Garden on a time walk from the Ordovician period to the present day. Families started at the time spiral and viewed an app animation that moved them through key landforms representing different periods of geologic time, used the app resources to place landforms in their appropriate geologic time, and engaged in various forms of immersion to support their understanding of the formation of the Appalachian landscape.

Sensory immersion supported families to engage in geoscientific talk and observations

Given the place-based focus of the app, our design work intended to support tactile and visual sensory immersion in the Children's Garden through prompts encouraging families to talk aloud about what they saw or noticed. For example, Lisa (mother) and Zoe (6-year-old girl) engaged in sensory immersion at the Sandstone Boulders microsite, prompted by the app.

After reading the app's text and the sensory engagement prompt (Fig. 2, line 1), both Zoe and Lisa engaged in the visual and tactile exploration of the rock's appearance. Although Zoe was also interested in things other than the rock's textures, such as an arthropod (line 3), Lisa guided Zoe's exploration back to sandstone. As the family continued to touch the rock, Lisa used a questioning strategy to bring in additional information about sedimentary rock (line 7) having pieces of other rocks within it (line 5). They also commented on the texture of sandstone through their tactile exploration (i.e., smooth/rough on lines 10–11) and on the effects of water on sandstone (lines 8–9; line 13). The sensory immersion that was encouraged by the observation prompts in the app encouraged Lisa and Zoe to engage in geoscientific observation of the sandstone boulders as they found evidence of erosion, deposition, and change over time.

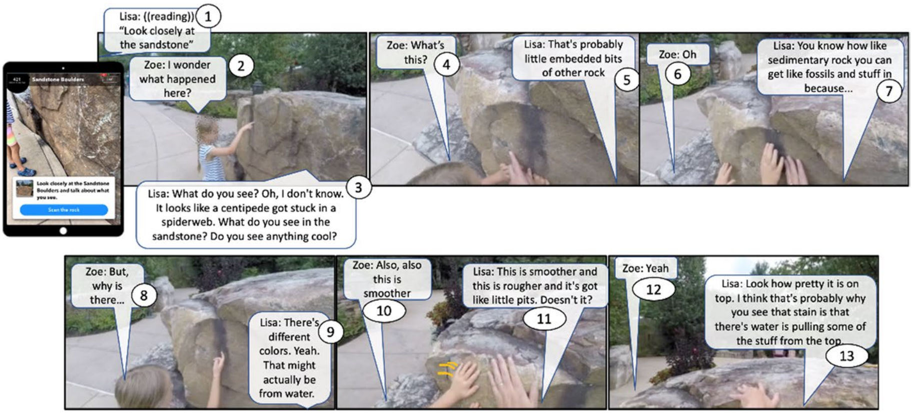


Fig. 2 Lisa and Zoe using the *Time Explorers* app to engage in sensory immersion at the Sandstone Boulders microsite

Multiple families engaged in sensory immersion at microsites throughout the app, often prompted by sensory engagement prompts or discussion prompts that connected geoscience features highlighted in the app to observations the family could make of the features within the Children's Garden. Although most family's sensory immersion was tactile, as shown in the vignette above, another family (mother, 11-year-old daughter, and 7-year-old son) engaged in auditory sensory immersion at the Model Cave, using the prompt "Look around—can you hear and see dripping water?" to pause and wait until they heard dripping water, as they would in a natural cave.

Actional immersion encouraged families' wayfinding, photo-taking, and engagement with the outdoor setting, which led to connections to the geoscience content

Time Explorers included multiple elements to foster actional immersion in ways that coordinated the families to make connections between the MAR app content and the Children's Garden setting, such as the GPS wayfinding map (Fig. 1), the app content (Table 2), and photo-taking activities. For example, Brendon (father), Andrea (mother), Lucas (6-year-old boy), and Mia (3-year-old girl) first used the GPS map to navigate to the Time Spiral Sculpture microsite. While navigating, Brendon held the iPad; he frequently shifted his attention between the digital map and the Children's Garden. He pointed and directed Lucas ("Cross this way to the time spiral.") to the wayfinding. Lucas was a partner in the actional immersion: He initially walked in the back, then walked side-by-side with Brendon to navigate with the iPad together, and later walked ahead of Brendon. Brendon continued to engage in the actional immersion, and he signaled to Lucas when the family was close to the microsite (i.e., pointing and saying, "See! See!").

All the families in our dataset were able to engage in the actional immersion of the wayfinding map to navigate from one microsite to the next. Because the GPS map marked families' movement, often families expressed excitement as they saw their movements tracked, leading to collaborative navigation and general engagement within the Children's Garden space. Even young children successfully used the GPS map for wayfinding to the next microsite. For instance, in one family with a preschool child, a mother, and a 5-year-old boy, the mother's attention shifted toward taking care of the 3-year-old. The 5-year-old then took the iPad and successfully used the GPS map for wayfinding to the next location, showing that the actional immersion was accessible to multiple age groups.

Another form of actional immersion was fostered at the Time Spiral Sculpture and the Model Cave microsites, where families received prompts from the MAR app to complete activities on-site. At the Time Spiral Sculpture, families were encouraged to start their journey by moving back in time, using an LOTM strategy to represent the time scale of geologic history. For instance, when arriving at the time spiral, Brendon read aloud the content about walking on the spiral to travel through time to find and photograph the Ordovician medallion. Andrea guided Mia and Lucas to walk the time spiral together to find the medallion (Fig. 3, line 1 and yellow arrows). Walking on the spiral, they paused at each medallion, which symbolized a different geologic time. For example, Mia repeatedly shouted "Seashell!" with excitement (lines 2–4, orange circle) when she (incorrectly) thought she reached the Ordovician period medallion.

The app also encouraged actional immersion in photo-taking of key elements of the outdoor microsite related to landforms and water bodies. For example, after Mia and Lucas' family found the actual seashell medallion representing the Ordovician period, the actional immersion prompt in the app asked them to take three photographs. Brendon encouraged Lucas to take the first photo (line 5) of the Ordovician medallion (Fig. 3, orange circle), and then Andrea suggested that Lucas include Mia's feet and the medallion in the photo (line 6, orange circle). Although this family was one of many that physically used their bodies to engage with the time-travel narrative and the physical space at the Time Spiral Sculpture microsite, this was the only family in our dataset that suggested that their children be part of the photographs for their journal—personalizing their experience in a way that was comfortable for their family. All other families curated their photos to only include the setting of the Children's Garden for their journal. All families were able to take photographs at each microsite as evidence of their observation.

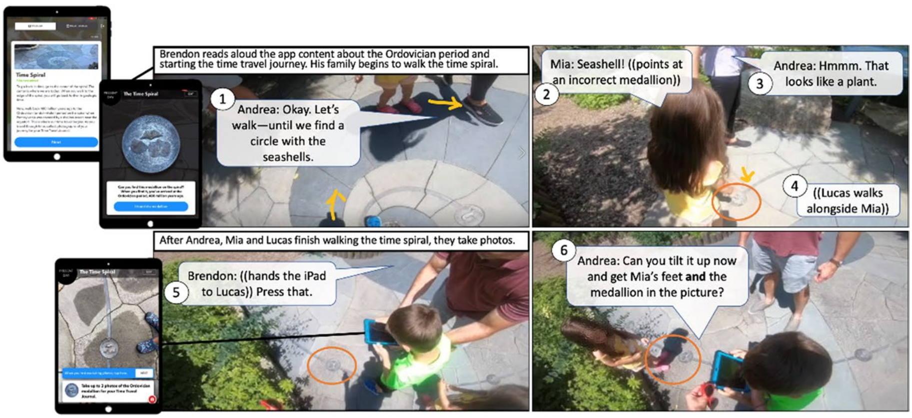


Fig. 3 Andrea, Mia, and Lucas collectively walk the time spiral to find the Ordovician medallion and take photographs

Social immersion, which was supported by discussion prompts, encouraged families' sense-making conversations

To support social immersion within families, our team designed discussion prompts that supported inquiry during the geologic time walk, which were followed by MAR elements within the app. The prompts included two shared family experience discussion prompts, one graphic representation discussion prompt, and four sensory discussion prompts (Table 1, column 3). The shared family experience prompts were designed to be culturally inclusive, taking a modified funds of knowledge approach (Moll et al., 1992), in which families' prior knowledge, shared memories, and cultural experiences were first elicited and then viewed as assets for science sense-making. The graphical discussion prompt was designed to support the understanding of a complex depiction of limestone and sandstone rock layers moving over time. Related to our sensory immersion principles, the goals of the sensory discussion prompts were to support collaborative conversations related to geoscience sense-making and observations.

One example of the use of graphic representation discussion prompts comes from one family—Jennifer (mother), Amanda (mother), Izzy (11-year-old girl), and Ethan (7-year-old boy)—who used the discussion prompt, "Look at this photo about how ridges form. Talk about what you learned" (Fig. 4, line 1) to support a conversation that involved all four family members building knowledge that limestone rock includes calcium that came from the bodies of sea creatures millions of years ago. Following the introduction of the discussion prompt, the family connected information across the garden—collectively synthesizing information from four (out of five) MAR microsites at the (human-created) Arched Wall (lines 2–3), which simulated the strata of sandstone, limestone, and other rocks. Through this conversation, Izzy, Amanda, Jennifer, and Ethan connected the sandstone (lines 3–5) and limestone (lines 6–10) in their community today (that makes up the visible ridges and valleys) to the prehistoric oceans with coral (lines 11–13) that covered the region millions of years ago.

As all families moved through the Children's Garden, they collaboratively discussed how Appalachia changed over geologic time, noting that Pennsylvania was underwater millions of years ago. Every family in the dataset had social discussions, spurred by the MAR app and its prompts; however, there was variation in the uptake of the social immersion. Sometimes, when a child was using the iPad, the child skipped over the discussion prompts

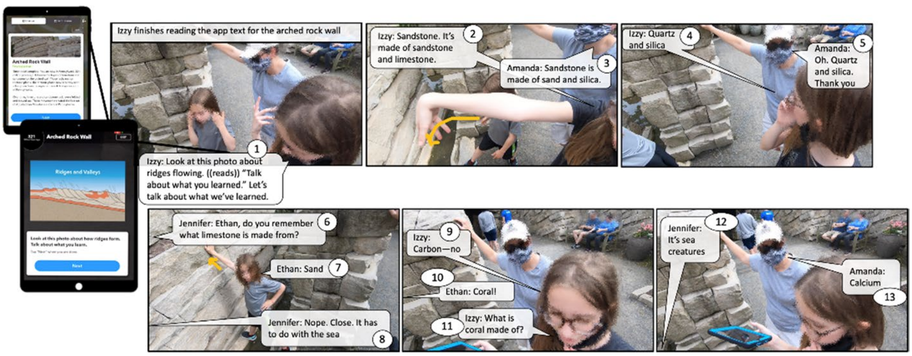


Fig. 4 Jennifer, Amanda, Izzy, and Ethan discuss limestone and sandstone rock at the Arched Rock Wall microsite

to get to the AR element in the app more quickly, with the result of less social immersion at that microsite. Some families engaged in every discussion prompt, while some were selective in the prompts they responded to. Most often, a parent or older sibling led the social immersion by speaking the prompts aloud, revoicing the prompts when necessary, and defining concepts for younger children through words and gestures.

Narrative immersion supported families in both their time-travel journey and geoscience sense-making

The app included an overarching narrative of families as time explorers who are exploring Pennsylvania's geologic history as they travel through time and collect photos for their time-travel journal, which was shown at the end of each microsite. We found that the narrative immersion supported families' engagement with the geoscience content, connecting the abstract ideas from prehistory to evidence in their community today.

Families were introduced to this geologic time narrative at the beginning of the app, and some parents helped to convey this narrative immersion to their children, as shown with Nicole (mother) and Luna (5-year-old girl). At the first interaction with the time-travel journal, Nicole framed the narrative for Luna (Fig. 5, line 1) saying that they were going on a trip through time and would put the photos she took into their journal for each microsite that they visited.

Nicole's and Luna's interactions during the next microsite, the Coral Sculpture, also contributed to the family's narrative immersion. Once Nicole read the text content aloud, the family moved on to taking pictures. Luna asked about the AR filter overlay that added blue-tint and floating nautili to the present setting when looking through the iPad's screen. Nicole explained this (Fig. 6, line 1), and Luna took photos. When they moved on to the journal, Nicole continued with the narrative immersion prompted by the AR filter, asking if she could imagine their community covered by an ocean (line 5). Although Luna initially said "no" (line 6), her later response asking about a nearby city (line 8) demonstrated how the AR filter aided her immersive experience.

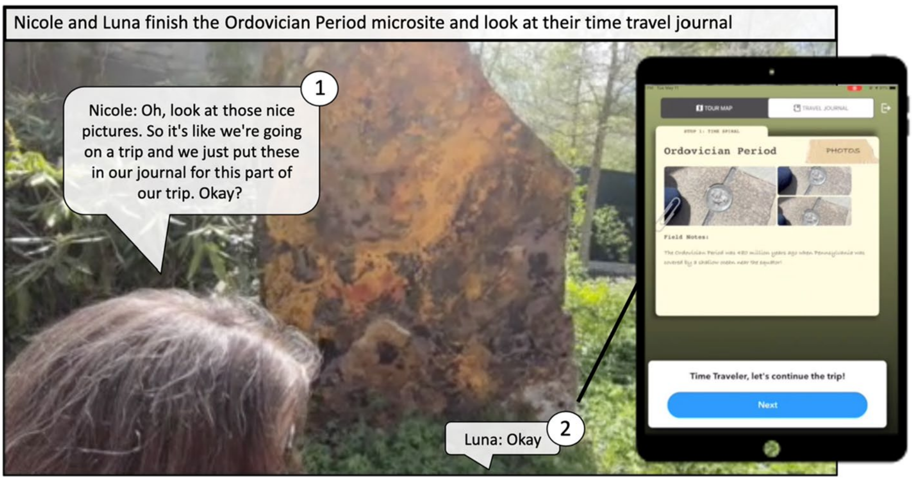


Fig. 5 Nicole explained the narrative of the time-travel journal to Luna

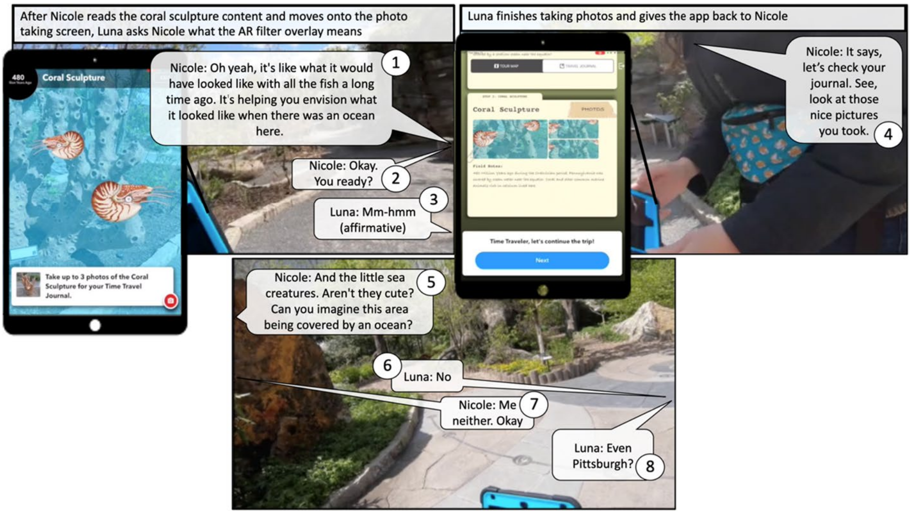


Fig. 6 With the help of a blue-tinted AR filter, Nicole and Luna explore a time when their community was underwater

In addition to the AR elements and journal in the vignette above, other elements of the app contributed to the families' narrative immersion. Multiple children uttered noises of excitement when seeing the spinning time spiral in between microsites showing that time was moving; one family invented a noise that they made when they saw the spinning mechanism. Overall, we found evidence that the time spiral animation facilitated families' engagement with the temporal aspects of the app, which supported their immersive interaction with the history of the local landscape. Not all families reported positive engagement with the metaphor; in one family's post-experience interview, the mother reported that her 5-year-old son was initially scared of the concept of time travel. This child was so immersed in the time-travel narrative that it made him nervous.

Sensory, actional, narrative, and social immersion worked together to support families' learning-on-the-move

These various forms of immersion (sensory, actional, social, and narrative) all worked together to support LOTM, as shown with Melissa (mother), Chloe (9-year-old girl), and Aiden (7-year-old boy). The following vignette at the In-and-Out Creek location demonstrates how the various types of immersion helped them to connect content from different microsites in the Children's Garden to the ridges and valleys of their community. It exemplifies how the immersive qualities of our MAR app influenced one family's understanding of geologic time and geoscience processes as they participated in LOTM processes (e.g., gestures to demonstrate erosion, pointing at imagined water flow, walking water pathways, and climbing rocks to curate photos that included a broad landscape view).

Interplay of narrative and social immersion from family members supported geoscience content

Families engaged in social immersion and narrative immersion by engaging in collaborative sense-making of the app content in ways that included talk and gesture. For instance, after Chloe read aloud the app content for the In-and-Out Creek, Aiden asked for clarification of what valleys are (Fig. 7, line 1), to which Chloe responded with hand gestures to indicate erosion and valleys and by repeating part of the app's text (lines 2–3). When Aiden asked for clarification about erosion (line 5), Chloe answered (line 6), but Melissa stepped in with a metaphor and gestures to explain the process of erosion (lines 7–9). Throughout this interaction, Melissa and Chloe worked together to support the social immersion of the family by connecting the app's content to shared family experiences that they could all understand.

Families also blended sensory and narrative immersion together as the story of their community's formation came alive with gestures, movements, and tactile exploration. While reading aloud the content about the paths at the In-and-Out Creek as an example of water gaps, Chloe initiated a series of full-body movements in which she and Aiden physically interacted with the microsite to imagine how ridges and valleys formed in the past. Tapping on one of the larger rocks, Chloe connected to the content in the previous microsite and talked about tectonic plates forming the mountains; meanwhile, Aiden climbed onto the rock and followed Chloe's movement (Fig. 8, lines 3–4). Then, Chloe visualized a valley by walking through the path between the rocks (lines 6–9), followed by Aiden and Melissa collectively using gestures to imagine where valleys and rivers could have been in the past (lines 9–12). In this case, their bodies in motion supported them in making sense of and immersing in the narrative of the community—specifically, the temporal and spatial relationship between ridges and valleys of the region. The In-and-Out Creek microsite,

Fig. 7 Chloe and Melissa use gestures and app content to support family science learning

Fig. 8 Chloe and Aiden use full-body movement to imagine how ridges, valleys, and water gaps formed in the past

representing a water gap, empowered the family's embodied exploration of local land formations at different scales.

Actional, sensory, and narrative immersive processes were manifested by blending content from the *Time Explorers* app and the physical setting of the microsite. At the end of this microsite experience at the In-and-Out Creek, Chloe, with Aiden's help (Fig. 9, line 1), took photos for their time-travel journal that best captured their observations from the In-and-Out Creek. She took several photos of the creek from the ground and then looked for the best spot to take their last photo, which would look down upon the ridges and valleys of the model water gap (lines 4–6). These actions demonstrated a combination of actional

Fig. 9 Chloe capturing the In-and-Out Creek through the photo-taking process in the app for their journal

immersion (photo-taking), sensory immersion (finding the best evidence), and narrative immersion (illustrating the story of the community's rock-water interactions) as Chloe captured the microsite photographically, within the confines of the app. It also aided the narrative immersion, as she took photos for their time-travel journal, connecting to the overarching narrative of being a time explorer and documenting the discoveries they made earlier.

This family vignette illustrates how different types of immersion came together and further enhanced one another in an embodied manner to support LOTM; it also demonstrates how various MAR elements (e.g., textual and visual content and photo-taking activities) could foreground the place as a resource to help the family make sense of local geologic history. Movement (such as erosion gestures, climbing and other full-body actions, and walking pathways of water flow) facilitated their immersive experience in the Children's Garden and communicated intention and meanings related to geoscience.

Discussion

Our investigation showed that families experienced immersion in ways that supported collaborative sense-making of geologic time scale and geoscience processes during their LOTM experiences in the Children's Garden with the *Time Explorers* app. Given the prior work in science-learning-based MAR (Kang et al., 2021; Georgiou & Kyza, 2021; Squire & Jan, 2007) that has focused on school learning or youths' school field trips, our analysis adds to the growing body of CSCL research on the thoughtful integration of technologies in informal and everyday experiences (e.g., Zimmerman & Land, 2022; Ha et al., 2021; Roberts & Lyons, 2017; Shapiro et al., 2017; Silvis et al., 2018). This focus on out-of-school-time learning is an important distinction given that visitors to informal spaces often come in heterogeneous age groups and may have existing relationships—with shared memories and experiences. As such, designing immersive XR for out-of-school-time learning requires a unique understanding of how the immersive elements influence families' LOTM and allow for deep connection with the digital materials. Designing various forms of immersion, especially social immersion, allows for the multiple meanings for place held by community members (Eijck & Roth, 2010; Lim & Barton, 2006; Semken, 2005) to be manifest in the families' discourse and embodied interactions.

Advancing LOTM with XR as a social learning theory for CSCL environments

Theoretically, our work further fine-tuned the role of LOTM as a social-learning process in an outdoor learning environment fostered by one form of XR, an MAR app. Prior work sought to understand the naturalistic perspectives of 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 social learning design conjectures blended with immersion suitable for CSCL environments (Table 2), so families' engagement in LOTM advanced their understanding of geologic time as they walked through the Children's Garden. By moving through eight microsites in the Children's Garden, each representing a different geologic period, families supported their temporal understandings of complex geoscience concepts. The families' gestures, coupled with talk in situ, provided an LOTM experience allowing participants to understand how water–rock interactions shaped their community's water bodies and landforms over millions of years.

The qualitative analyses of the vignettes (Figs. 2, 3, 4, 5, 6) illustrated how MAR supported scientific observations and family conversations that integrated complex geoscience concepts. Prior research (e.g., Cervato & Frodeman, 2012) has shown that developing geoscience understanding can be challenging; however, families' movements supported them in connecting to multiple MAR microsites (e.g., Jennifer, Amanda, Izzy, and Ethan and Melissa, Chloe, and Aiden)—so they collaboratively built complex understandings of how water, sandstone, and limestone interacted to create their community's present landscape.

The role of immersive design and pedagogy to support social learning with XR: Advancing the immersive, family-centered, place-based LOTM design framework

Given the importance of sensory observations in outdoor learning (Ballantyne & Packer, 2009; Beery & Jørgensen, 2018) and science education (Eberbach & Crowley, 2009), we found evidence that using the social and sensory immersion elements of our MAR app encouraged visual and tactile observations in the Children's Garden. The MAR digital content supported, and did not distract from, families' outdoor explorations (e.g., Lisa and Zoe and Melissa, Chloe, and Aiden). In fact, all the families in the study engaged in the tactile and visual observation of concepts related to geologic time scale in response to the *Time Explorers* prompts and activities. The app's four sensory discussion prompts also encouraged families to notice the textures of limestone and sandstone rocks and locate visual evidence of water gaps, rock strata patterns, and erosion. The geoscience representation encouraged some families to integrate the prior microsites with the image in front of them (e.g., Jennifer, Amanda, Izzy, and Ethan). Although the discussion prompts were critical to stimulate discussion and focus observations on meaningful geoscience concepts, emergently families such as Nicole and Luna brought in prior trips (i.e., Pittsburgh), their goal in curating photos (e.g., Brendon, Andrea, Lucas, and Mia and Melissa, Chloe, and Aiden), and interests outside of the geoscience content (i.e., centipedes—Lisa and Zoe). The presence of these emergent conversations during the *Time Explorers* designed experience illustrates the importance of leaving space for families' prior knowledge, agendas, and culturally important experiences when designing for social immersion in CSCL.

We found evidence of the effectiveness of actional immersion. In contrast to prior studies that have shown that learners often experience technical problems navigating AR (Akçayır et al., 2017), we found that all families were able to seamlessly use the GPS navigation for wayfinding through the garden and the in-app photo journaling functionalities as intended. However, some families intentionally or accidentally skipped over discussion prompts (and occasionally, an AR animation). This suggests a need to refine strategic support and app navigation for future iterations while also honoring the importance of families' free choice about how much learning support they want.

The narrative storyline, in concert with MAR elements, allowed us to connect the various physical locations within the Children's Garden in a conceptually rich way for understanding geologic time. Rather than designing the app to provide isolated science content about a specific exhibit or artifact, the narrative immersion provided an anchor to which we could connect broader conceptual explanations of geologic time.

Notably, the various forms of immersion often worked together as redundant and synergistic scaffolds to provide similar learning supports for families' LOTM processes at different microsites or in different manners, respectively (Tabak, 2004). Having multiple types of immersion (often social plus another form but also narrative plus another form) also enhanced the experience of families' immersion, supporting family members in imagining together (Figs. 6, 7), engaging in full-body playful movement (Figs. 3, 8, and 9), and participating in joint attention toward observing key features of the setting (Figs. 2, 4, and 8).

Taken together, our analyses support informal education practice by elucidating how the MAR app's visualizations, photo-taking activities, and discussion prompts could be successful tools in an app designed for families' outdoor learning (e.g., Figs. 2, 3, 4, 5, 6). Although narratives, photo-taking, and discussion prompts have been used in informal spaces in prior work (e.g., Georgiou & Kyza, 2021; Kawas et al., 2019; Klopfer & Squire, 2008; Ryokai & Agogino, 2013), our research adds to the utility of these tools while LOTM during outdoor education experiences and to support geoscience 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 observations and conversations to reflect on their observations as they moved through the Children's Garden; these tools were easy to deploy on an MAR app while moving.

Next steps in Time Explorers to further enhance immersion

Our work is centered on key geoscience principles (land–water interactions) that are important for rural families' daily lives in understanding water access and quality, underground mineral rights, and sustainable development (including building to avoid sinkholes). Based on this analysis of our case study families and the design conjectures in Table 2, we suggest the following changes to our design. These recommendations could be applied to other MAR or XR designs to create immersive, family-centered, place-based LOTM experiences.

- Although some families connected various sensory content from multiple microsites emergently [such as the two kinds of sedimentary rocks (Zoe and Lisa) and layers of rock strata (Jennifer, Amanda, Izzy, and Ethan)], to better support all families' sensory engagement, we will design future sensory prompts or geosciences representations to foster comparison across specimens and landforms.
- As shown in Figs. 2, 3, 4, 5, 6, 7, 8, 9, all families read the text aloud. As such, we would streamline and reduce the amount of text.
- As shown in multiple families (Nicole and Luna; Brendon, Andrea, Lucas, and Mia; Melissa, Chloe, and Aiden; and Lisa and Zoe), the ability to personalize tasks and experiences based on interests, prior knowledge, and goals for learning was important. We will add more family experience discussion prompts to our MAR app to support more exploring and investigating areas of interest.
- Given the role of family gesture and movement (see arrow and lines in Figs. 2, 3, 4 and 7, 8, 9), we would simplify some of the actional immersion tasks to (a) leave space for family-directed movements and desired physical engagement with the space (see Chloe and Aiden) and (b) better balance families' interest in participating with the digital MAR experience and engaging with the physical Children's Garden setting.
- Based on the discursive work that Nicole and Luna did to unpack the time-travel narrative, we would provide further immersive elements at the initial microsites (such as the Coral Sculpture and Time Spiral Sculpture) to create stronger narrative and actional immersion throughout the MAR experience.
- We did not find evidence of emancipatory immersion in our dataset, so our next design iteration will include stronger connections to the sociocultural history of the area by including features such as (a) short videos from stakeholders across multiple scientific

disciplines and community members, representing key environmental justice concerns, and (b) sources for connecting with community-based anti-racist and justice organizations.

A separate goal for future MAR designs is to create a collection of apps, with our partners at the Arboretum and the families in the area, that are thematically tied and that progressively deepen exposure to science concepts grounded in community. Previously, we developed another app (*Cave Explorers*; Zimmerman et al., 2020) that together with this app (*Time Explorers*) set the stage for understanding complex geoscience forces that create caves, sinkholes, underground water, springs, and similar karst landforms. By linking these two short apps together on a conceptual topic, we give families more opportunities to deepen their learning and time to engage in emancipatory immersion as advocated by Enyedy and Yoon (2021). For instance, a third app in this series could reinforce community connections to the geoscience content, allowing families to focus on local issues of water quality and environmental stewardship.

Finally, given that our study population oversampled white families, another next step is to work with our community partners to ensure we include a broader representation of community members in our future studies. Working with an even broader constituency of community members will allow *Time Explorers* to support more families to engage in storying the landforms and water bodies (Marin & Bang, 2018) that are present in their community.

Acknowledgements This material is based upon work supported by the National Science Foundation under Grant No. 1811424. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Thanks to our app development team of Nicholas Rossi, Markus Fürer, & Bart Masters, as well as colleagues Charles Q. Keith, Lucy R. McClain, Stephanie Bowles, and Katie Grills. We appreciate the staff and volunteers at the Arboretum at Penn State for their continued involvement in our educational research. Finally, many thanks to the families who participated in our study during a challenging pandemic time; their commitment to each other and to continuing to learn was an inspiration to us every time we watched their videos and read their transcripts.

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