JrnlID 11412_ArtID 9315_Proof# 1 - 15/02/2020

International Journal of Computer-Supported Collaborative Learning
https://doi.org/10.1007/s11412-020-09315-5

Distributed spatial Sensemaking on the augmented reality sandbox

Yotam Hod[1] • Daniel Twersky[1]

Received: 31 July 2019 / Accepted: 6 February 2020

Abstract
This research examines small group collaboration on the Augmented Reality (AR) Sandbox, an interactive, real-time topographical simulator that provides a color layer of augmentation showing depths and height, contour lines, and hydrology vis-a-vis the terrain of sand in a box. Prior research has focused on AR Sandbox activity designs, outcome measures, and user's perceptions of different usability functions. No research to date has examined the situated processes by which groups engage in CSCL activities on the AR Sandbox as they participate in authentic forms of topographical studies. Taking a dialogic stance to examine CSCL using AR, in this study we draw on previous scholarship about distributed spatial sensemaking to analyze the way groups interact over material, social, and activity contexts. Based on an Interaction Analysis methodology, our findings point to the different resources that are coordinated with the use of the AR Sandbox; the different ways that turn-taking during distributed spatial sensemaking occurs; and the intricacy and speed by which multimodal resources are used to advance spatial thinking. The implications of this research broaden views of distributed spatial sensemaking, provide novel methodological tools to examine this phenomena, and suggest different levels of analysis and expectations for studies on the AR Sandbox.

Keywords Augmented reality sandbox · distributed spatial sensemaking · interaction analysis

Introduction

The past two decades have seen a surge in Augmented Reality (AR) devices across formal and informal learning settings (Cuendet et al. 2013; Yoon et al. 2018). The promise of AR is

✉ Yotam Hod
yhod@edu.haifa.ac.il

Daniel Twersky
danielt450@gmail.com

[1] University of Haifa, Israel, Haifa, Israel

particular to STEM (Yoon et al. 2012), due to its unique affordances including making the invisible visible, allowing people to explore dynamic representations, detailing scientific phenomena, interactivity, embeddedness in authentic tasks, scaffolding, and collaboration (Yoon and Wang 2014). One of the most promising and widespread of these AR devices is the AR Sandbox, an interactive, real-time topographical simulator that provides a color layer of augmentation showing depths and height, contour lines, and hydrology (i.e., rain flow), vis-a-vis the terrain of sand in a box (Kreylos 2016). It is widely believed that spatial thinking—an inseparable and vital facet of topographical competence—has the potential to be developed by users of AR Sandboxes (Richardson et al. 2018; Vaughan et al. 2017).

There are currently hundreds of documented AR Sandboxes around the world,[1] including numerous commercial companies that manufacture and sell them.[2] Despite their popularity and allure, research investigating student learning as they interact with the AR Sandbox lacks a strong theoretical and empirical basis. This type of research is important not just to examine if using the device supports learning, but to understand how it does, as well as how to further develop its potential. In this paper, we take the view that the spatial thinking involved when using AR Sandboxes is distributed across material, social, and activity contexts in a process referred to as distributed spatial sensemaking (DSS: Ramey and Uttal 2017). Using this lens, we ask, *how is spatial sensemaking distributed across small collaborative groups when they interact around the AR Sandbox?*

What is the AR sandbox?

AR is as an additional layer of information—which can include one or more senses—on the real world using a computer (Danish et al. 2015). The AR Sandbox is comprised of several instruments: A sand table, Microsoft Kinect 3D camera, imaging software, and a projector. The changes that the user makes and which are projected on the sand are received through the system by the Kinect camera. The software reads the elevation of the sand and used the digital projector to augment it by adding color, altitude, latitude topography, and water simulations (Fig. 1). As a system, it allows users to create topographical models by designing them on actual sand with their hands, as well as create digital water that follows gravitational principles by placing their hand between the sand and the projector in the relative position of a cloud (Kreylos 2016).

Existing research on the AR sandbox

Researchers or users of the AR Sandbox have suggested that it can benefit learning, particularly in relation to STEM goals (Reed et al. 2014). For example, Woods et al. (2016) claim that the sandbox may support core scientific practices outlined by the Next Generation Science Standards. Other researchers have pointed to the expected benefits for teaching geological concepts (Sánchez et al. 2016) as well as its potential to develop students' spatial thinking skills (Richardson et al. 2018). To clarify the empirical claims so that we can build on existing knowledge about the AR Sandbox, we have summarized all published materials that we could find on it (see Table 1).

[1] https://arsandbox.ucdavis.edu
[2] Worthington Direct, iSandbox, Topobox, etc.

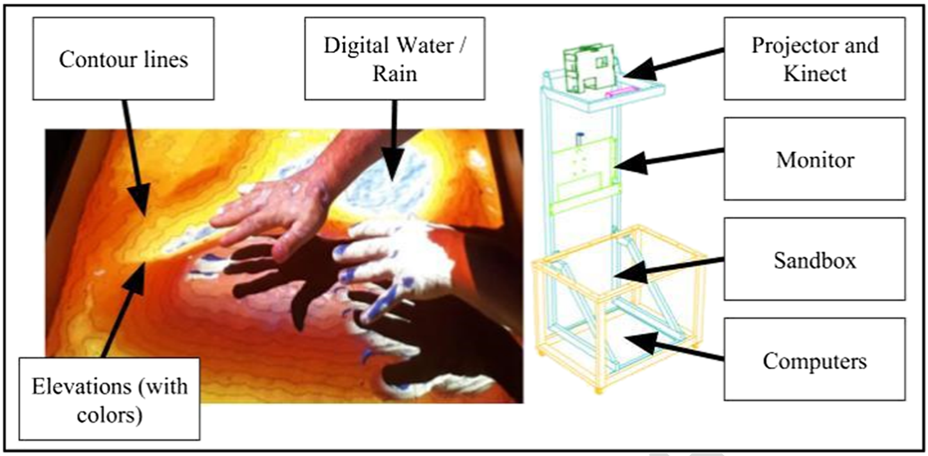


Fig. 1. Augmented features on the AR sandbox (left); Structure of the AR Sandbox used in this research with a monitor added for instructional purposes (right)

In our review of this literature we found three categories of published research on the AR Sandbox. The first category focuses on the pedagogical potential of the sandbox, either analyzing its technological affordances (Sánchez et al. 2016) or suggesting a conceptual framework that can be used to develop curricula around it (Bandrova et al. 2015). These cases do not rely on new empirical data.

The second category of studies is empirical, with a primary data collection method asking students to complete questionnaires based on their experience. Woods et al. (2016) administered exit surveys to assess if users thought the AR Sandbox improved their learning. Part of their results showed that "students were universally positive (97%) in their perception of the helpfulness of the AR Sandbox for understanding topographic maps and superficial features and processes" (pp. 209–210). Vaughan et al. (2017) similarly examined perceived learning, but also included an assessment of engagement through the use of questionnaires. Their results were generally positive, with 75% of students indicating that use of the AR Sandbox improved their understanding of certain geological features. Darley et al. (2017) investigated the AR Sandbox from the perspective of usability, user experience, and adaptability (in contrast to learning). In addition to questionnaires, the researchers carried out observations during use of the sandbox on these three constructs.

The third category involves experimental design. For example, Richardson et al. (2018) sought to examine the outcomes of using the AR Sandbox to study topographic maps as well as develop spatial thinking skills. Two treatment groups—AR and non-AR—engaged in 20 min of multimedia instruction followed by a set of activities based on which treatment group the subjects were a part of. Post-test results showed that activities using the AR Sandbox led to significantly better gains in topographical comprehension. The study suggested that the affordances of the sandbox, including embodied interaction, multimodal sensory inputs, and dimensionality differences, were a factor in this improvement. The researchers also examined two rival hypotheses about whether the graphical affordances would better support learners with high spatial abilities (spatial ability as enhancer hypothesis) or low spatial abilities (spatial ability as compensator hypothesis), neither of which were supported by the results. Other outcomes-based studies, including Evans, Fleming, and Drennan (Evans et al. 2018) and Giorgis et al. (2017), did not show any significant positive effect of using the AR Sandbox.

t1.1 **Table 1.** Summary of published research on the AR Sandbox.

	Categories of studies	Citation	Summary of Research
t1.2	**Categories of studies**	**Citation**	**Summary of Research**
t1.3	Pedagogical	Bandrova, Kouteva, Pashova, Savova, & Marinova, (2015)* Savova (2016)*	Elucidated a conceptual framework that can be applied to the development of curriculum and activities using the AR Sandbox
t1.4		Sánchez, Martín, Gimeno-González, Martín-Garcia, Almaraz-Menéndez, & Ruiz, (2016)* Kundu, Muhammad, & Sattar, (2017)*	Elucidated the technological affordances of the AR Sandbox for educational use
t1.5	Empirical, based on self-report of students (as well as observation in the case of Darley et al. 2017)	Woods, Reed, Hsi, Woods, & Woods et al. (2016)	Examined students' perceptions of the effectiveness of the AR Sandbox as well as the reasons they gave for why it was effective
t1.6		Vaughan, Vaughan, & Seeley, (2017)	Examined student engagement and their perceived learning
t1.7		Darley, Tavares, Costa, Collares, & Terra, (2017)*	Investigated different aspects of the user experience
t1.8		Afrooz, Ballal, & Pettit (2018)*	Used online questionnaires to measure sandbox usability, decision-making, prioritizing design interventions, and idea negotiation among users in a workshop.
t1.9	Empirical, outcomes-based	Richardson, Sammons, & Delparte, (2018)	Examined an AR Sandbox versus non-AR Sandbox condition to examine the effect on topographical map skills, including mental rotation
t1.10		Evans, Fleming, & Drennan (2018)	Examined outcomes on type of spatial thinking using the AR Sandbox using pre- and post-tests between two groups (AR group versus map group)
t1.11		Giorgis et al. (2017)	Examined outcomes on map reading skills using the AR Sandbox versus a control group, checking along various dimensions (gender, prior abilities, etc.)

**Published in conference proceedings.*

The combined results of these studies tells us a few important things regarding the use and potential of the AR Sandbox, but also leads to many open questions and a clear need for a different research stance. The research does indicate, from all of the empirical studies, that the AR Sandbox *could* have a positive effect on learning generally, and spatial thinking specifically. The three self-report studies are merely suggestive, yet the fact that students overwhelmingly and repeatedly claim that using the AR Sandbox improves their learning indicates that there is an important phenomenon to elucidate and better understand. Richardson et al.'s (2018) experimental study is similarly suggestive because it is a single study of outcomes and more are needed to demonstrate that these results can be replicated. Moreover, although the researchers showed results that the AR intervention was better than more traditional methods to teach topography, there are some undiscussed limitations. First, their intervention was short.

To see deeper effects we would anticipate that an extended set of activities over a series of days or weeks would be needed. Second, consistent with Yoon et al.'s (2018) approach to AR, we would anticipate that any significant effect would be a result of a combination of scaffolds including AR, but also around collaborative knowledge building. The three outcomes-based studies do not detail any of the non-AR scaffolds, let alone the activities that the students in the treatment group engaged in. Both of these points, when considered together with the self-report and pedagogical studies, show the lacuna in AR Sandbox research. What is needed are nuanced and situated measurements of the processes of learning during activity with the AR Sandbox to gain insight into how and why it could lead to more advanced forms of spatial thinking.

The need for situated approaches to examine topographical thinking

Our goal in this research is to expand conceptualizations of the way groups use the AR Sandbox in their topographical studies so that the way it mediates spatial thinking can be better understood and designed for. By topographical studies, we refer to the scientific field within the geological sciences whose purpose is to map the structure and landforms of terrains by precisely illustrating and describing land configurations, heights, measurements, distances, and orientation relations in space (Florinsky 2016). This field fundamentally deals with representing three dimensional surfaces in two dimensions, a fact that has changed dramatically in recent years with technological developments like augmented and virtual reality (Carbonell, and C.,, and Asensio, L. A. B. 2017). Topographical maps allow readers to obtain a general representation of designated areas for planning and decision making, or for specific purposes, such as navigation (Markoski 2018).

Spatial thinking has an established interrelation with the study of topography because topographical maps are two-dimensional representations of three-dimensional surfaces (The National Research Council 2006). In recent years, Newcombe and Shipley (2015) synthesized the diverse views on spatial thinking and in-so-doing suggested a two-by-two typology. One dimension includes a differentiation between spatial representations that are *intrinsic* with those that are *extrinsic*. Intrinsic refers to inseparable parts of objects (their forms and their base parts); extrinsic refers to the relations between objects and their frames of reference. For example, the difference between a hill and an extension are intrinsic, whereas spatial relations between them and other spatial structures are extrinsic. On the other dimension, each of these types of spatial thinking can be represented *statically* or *dynamically*, such as when an object is rotated or bent, or when it is moving. The resultant categories include (a) intrinsic-static; (b) intrinsic-dynamic; (c) extrinsic-static; and (d) extrinsic-dynamic. When people apply their spatial thinking in practice, they often use combinations of these capabilities. Table 2 demonstrates how these four spatial thinking categories relate to the 2D and 3D representations involved in studying topography on the AR Sandbox.

While spatial thinking has traditionally been thought of as a fixed cognitive ability that occurs in decontextualized activity, new evidence has emerged in recent decades contradicting this assertion. In a meta-synthesis of research, Uttal et al. (2013) show clear results supporting the notion that spatial thinking can be influenced by environmental factors. A contextualized and malleable perspective not only runs against deficit views of learning (Keifert and Stevens 2019), but suggests that situated views can shed light on some of the intricate, micro-level processes involved in spatial thinking.

t2.1 **Table 2** Two-by-two typology of spatial thinking

	Category of Spatial thinking	Abilities and competencies derived from category	Example using a 2D representation (e.g., topographical map)	Example in a 3D terrain
t2.3	Intrinsic-Static	Require the identification, description, and classification of objects. This includes the ability to decompose objects into parts and examine each element separately or as part of the object.	A person identifies the object they want to locate and characterizes relevant details that help it fit into a category. For example, a circle with several internal circles is considered a hill.	A person examines the landscape and, according to the structures that they see, distinguishes objects from each other to identify them. For example, two elevations that meet at a crest may be identified as a hill.
t2.4	Intrinsic-Dynamic	Requires several interrelated capabilities having to do with objects and their transformations. One key component is the ability to imagine objects as they transform from their two-dimensional to three-dimensional views, and vice versa. In addition, the ability to perform a mental transformation includes rotating, folding and bending the object and its parts. Similarly, this includes being able to visualize what shapes would look like if they were cut into slices and viewing the cross-sections simultaneously for comparison. Finally, this can include the ability to imagine changes of objects over time.	A person notices a circle with several internal circles and imagines it as a hill in three dimensions.	A person can imagine transforming an object that they see. For example, they may look at the beginning of the slope of the mountain into a valley, and visualize its continuation without seeing its end.
t2.5	Extrinsic-Static	Requires describing the location of objects and their position relative to other objects and the self in space. This allows for comparisons of many different types. For example, the relative size and scale of objects can be compared. This relates to mapping abilities as the relation of objects to one another can also be represented on maps. This can also include understanding the downward flow of water in relation to gravitational force.	A person compares two points on the map and imagines which is higher or lower in elevation, or may consider the flow of water (watershed) between the two.	A person determines the position of objects relative to one another. For example, they can recognize that they are now within a valley between adjoining hills, or that one hill is further north than the other.
t2.6	Extrinsic-Dynamic	Often referred to as perspective-taking (Newcombe and Shipley 2015), this refers to the ability to visualize object relations with regard to the self as they are in continuous motion. This allows people to maintain stable representations of the world-in--action.	A person positions themselves on the map in relation to the objects in the terrain and on the map. For example, they may trace a navigational route along a ridge while imagining what they may be seeing.	As a person moves through a terrain, they maintain an accurate understanding of where they are in relation to the topographical map.

A dialogic approach to investigate the AR sandbox

As a field, CSCL has embraced post-cognitive perspectives that acknowledge the social, historical, and cultural contexts of learning (Stahl 2012). Arnseth and Ludvigson (Arnseth and Ludvigsen 2006) distinguish between systemic and dialogic approaches within CSCL. Systemic approaches focus on social interaction with technologies, with the goal of describing how different features of the system may facilitate or constrain certain learning outcomes. This approach is related to what Stahl (2012) refers to as socio-cognitive. In contrast, dialogic approaches do not separate between contexts and cognition, but view them as intertwined and co-mediated. A requirement of dialogic approaches is to look beyond the immediate situation because activities are responsive to and inseparable from those before them and as part of broader contexts (Arnseth and Ludvigsen 2006). This view is typically considered a sociocultural approach (Rogoff 1995), rooted in the work of Bakhtin (1986) and Vygotsky (1978).

Research on AR in CSCL is divided between systemic and dialogical approaches. Yoon and colleagues, for example, published a number of studies investigating different ways that AR can scaffold cognitive outcomes. Working in a museum setting, Yoon et al. (2012) researched how an AR system involving students embodying a circuit could help them understand scientific phenomena. Yoon et al. (2018) similarly designed a controlled experiment where the conditions included an AR system that helped students visualize magnetic forces. The results of several studies along these lines showed how collaboration could be supported through digital augmentation. These studies were systemic, focusing less on how collaborative groups *think with* the AR, and more on the cognitive outcomes of doing so.

In contrast to the Yoon studies, Enyedy et al. (2012) extended accounts of AR by mostly taking a dialogic stance. In one study, they used AR in a project wherein young students embodied the properties of physical objects in reaction to various forces through socio-dramatic play. The AR involved a device that recorded and displayed students' movement on a whiteboard. For example, a student would embody the movement of a ball in reaction to several forces placed on the carpet. The rest of the community watched the student's movement and shared, critiqued, and refined her embodied predictions. Part of this study involved tracking individual students' predictions and explanations, taking into account the various resources that the students drew from (e.g., those that were embodied and in semiotic forms). In a follow up study based on the same Learning Physics Through Play project, Enyedy et al. (2015) offered a liminal blends framework to pinpoint, through microgenetic analysis, how AR artifacts were used in conjunction with other resources. The liminal blends framework built on views that cognition is distributed by focusing on the way students align the resources they interact with in complex spaces. Whereas both studies acknowledged the social and material roles of learning, the latter study in particular extended the previous one (and previous formulations of the framework) by focusing on the dialogic space between individuals, material resources, others, and shared cultural histories.

Our study aims to extend accounts of dialogical spaces within AR settings by focusing on small groups and with a technology that is highly conducive for CSCL. As argued by Stahl (2012), CSCL can be examined at various levels of analysis, revealing different insights. Koschmann (2018) points to group level phenomena like correction, repair, and social organization such as turn-taking as vital aspects of intersubjectivity. The AR Sandbox is well-suited for micro-analytic studies to investigate such phenomena given its size affordances (several users), multi-touch capabilities, and the integration of multiple representational forms (e.g., 2D and 3D). Previous CSCL studies using AR have acknowledged the distributed nature of learning and have contributed new ideas with their studies (i.e., liminal blends). Yet, analyses that foreground small group functioning are still missing. Studying how learning is achieved with students in partnership with others and using culturally-provided tools can therefore advance the field's conversation about AR from dialogic perspectives.

A distributed spatial Sensemaking framework

To conceptualize spatial thinking as a contextualized and situated activity from a group level (Lave and Wenger 1991; Rogoff and Chavajay 1995), we draw on Ramey and Uttal's (2017) DSS framework to view the cognitive aspects of spatial thinking as distributed across material, social, and activity contexts when studying topography. This approach brings together "multiple theoretical lenses from the learning sciences in order to improve our understanding of the role of spatial thinking… result[ing] in a richer, more authentic, and a more complete understanding of this complex learning phenomenon" (p. 283).

If we consider the AR Sandbox as an object or tool that supports spatial thinking, we ought to consider some of the significant material and social mediators of learning within activity contexts. The focal material object that can be acted on as part of AR Sandbox activities is the digitally augmented sand. The interactive aspect of the sand is one of the AR Sandbox's core features as a tangible-user interface. Decades of research in informal learning settings has repeatedly shown that such reciprocity between the user and the material object results in greater enjoyment and interest, increased cooperation, and overall better user experiences (The National Research Committee 2009). The ability to manipulate objects and have them respond provides real-time feedback to the user. The digital augmentation features, in particular, allow for computational ideas to be represented intuitively (Ishii 2008).

Research on the AR Sandbox has yet to develop a framework for the hands-on aspect of the tool, namely the way the users manipulate the augmented sand. To create a framework for the dynamic manipulation of this material context, we adapted Steinhardt's (1998) description of various sand functions into a framework that could be tested empirically. Table 3, Table 4 and Fig. 2 describe and illustrate, respectively, different possible sand actions that can occur on the AR Sandbox.

In addition to the material context, the social context includes users referring to spatial features and object properties that describe their dimensionality (e.g., big, small, thin, etc.), shape (e.g., circular, triangular, etc.), and their spatial properties (e.g., straight, jagged, flat, edge, etc.). This type of discourse has been referred to as spatial talk (Pruden et al. 2011). This aligns with other views, such as Ramey and Uttal (2017), who define it as a category of spatial sensemaking that involves "discussing shape, orientation, position or movement of objects, groups of objects, or representations" (p. 289). We view spatial talk consistently with these perspectives, as expressions about one or more objects and their features or properties.

Like spatial talk, spatial gestures are important social aspects of spatial thinking using the AR Sandbox. According to Goldin-Meadow et al. (2012), a gesture is:

> ...a unique interface between the motor system and more abstract representations. It can convey information that is strategic to solving the task and is stripped of the sensory-motor constraints of a fully realized action (including constraints imposed by the outcome of the action), while still being rooted in the motor system (p. 877).

Spatial gestures are consistent with this definition, but are specific to endeavors relevant to spatial thinking. For example, a person who waves their hand conveys information appropriate

Table 3 Spatial actions on the sand

Type	Action	Description
Using the surface	Gathering	Creating a mound which either merges into the surrounding sand, another mound, or at the edge of the sandbox
	Carving	Creating boundaries demarcating territory or the start of a purposeful path using curved or straight lines
	Impressing	Pressing down on the sand to make an imprint or to make an object more compact
	Flattening	Aligning the sand surface by spreading it out until there is no trace of the shape that existed beforehand
Penetrating the surface	Digging	Creating holes in the sand
	Tunneling	Removing sand that is located beneath existing sand
	Burying	Concealing an object under the sand
	Revealing	Removing sand from a concealed object so it can be seen
Use of water	Raining	Releasing small amounts of digital water
	Flooding	Releasing water beyond the quantity that the sand can absorb
	Drying	Removing the area filled with water to expose the ground beneath it (completed through an automated function on the computer in the AR Sandbox)
Regarding the surface	Pointing	Direct someone's attention toward an object on the sand by extending one's finger

to the task of welcoming another subject or terminating an interaction. As these are not relevant to spatial thinking, they would better belong to a general category of gestures and not those that are spatial. In contrast, spatial gestures are "grounded" in the spatial task, conveying information about their physical referents or actions (Alibali and Nathan 2007). In a review of literature on gestures, Ramey and Uttal (2017) distinguish between static spatial gestures with those that are dynamic. Static spatial gestures represent objects that do not move; dynamic spatial gestures represent objects that do move.

The activities within which the material and social contexts take place are consequential. Fostering spatial thinking requires groups to collaborate in a disciplinary way of thinking and enculturating its practices and norms (Brown et al. 1989). Activities need to be designed so they are authentic to the intended disciplinary culture with considerable support and time for us to expect them to achieve deep levels of understanding of complex topics (Hod and Sagy

Table 4 Stages of AR activities during meeting two of focal group

Stage	Title	Description	Duration
1	Eliciting prior knowledge	Group engaged in a conversation around the monitor and sand (without the AR) where they asked questions, elicited their prior knowledge, and made assumptions about topography.	00:00–06:36
2	Diffusion, exploration, and coordination	After turning on the AR, the group played with several of its functions and tried to coordinate (verbally and non-verbally) how to have a group conversation.	06:37–10:45
3	Connecting representations	Group began a shared conversation focused on comparing the 2D map with the augmented sand.	10:46–16:11
4	Fine tuning	Group decided to redefine their concepts and became more precise with the sand.	17:00–20:24
5	Using the water	Group began to use the water feature of the AR Sandbox deliberately to analyze their relation to the concepts they had thus far examined.	20:25–35:18

*The 49 s between stages 3 and 4 involved a technical matter where water needed to be sprayed on the sand and therefore did not involve relevant DTS

JrnlID 11412_ArtID 9315_Proof# 1 - 15/02/2020

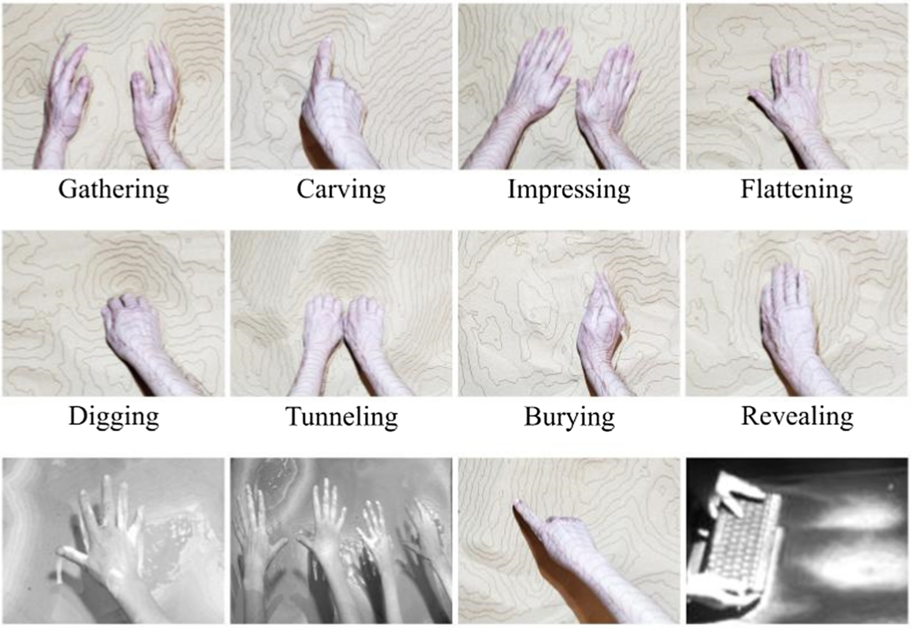


Fig. 2. Illustrated spatial actions on the sand on the AR Sandbox (colors on the AR Sandbox were removed to increase clarity)

2019). To advance our understanding of CSCL, we view the small group as the unit of analysis for these authentic activities. The type of AR Sandbox activities that we have designed enable groups to engage in disciplinary-like forms of social interaction with relevant material objects. In the context of topography, this means that groups explore two and three dimensional representations of terrains using expert tools through developmentally appropriate, guided inquiry.

Methodology

To investigate the interaction of collaborative groups of students as they use the AR Sandbox, we carried out an Interaction Analysis (Jordan and Henderson 1995). This method is appropriate because it is based on the assumption that cognition is distributed socially and ecologically, with the goal of identifying the ways that "participants utilize the resources of the complex social and material world of actors and objects within which they operate" (p. 41). Interaction Analysis ultimately produces ecologically valid case studies that illustrate collaborative meaning making across human activities, artifacts, and technological tools (Stahl et al. 2006), at fine-grained levels of detail that include complex features such as overlapping activities of several participants or the re-engagement of intellectual or material resources used earlier by other group members. Ultimately this methodological approach has allowed us to elucidate different ways that small collaborative groups using the AR Sandbox interact within their material, social, and activity contexts.

Research setting and participants

This study was conducted as part of a research-practice partnership (RPP: Coburn and Penuel 2016) where we worked closely with a teacher over several years at a boarding academy in Northern Israel for high-school aged students. One of curricular goals set out by the school is for students to learn how to navigate independently in unknown terrains with the guidance of 2D topographical maps. In preparation, students take courses on topography which, before the onset of this research project, were taught using instructionist methods (Sawyer 2014). In general, the teacher would draw and explain topographical concepts to the students on the white board in the front of the room, and after approximately eight meetings students were evaluated on a paper-and-pencil test before going out to the field for the navigation.

In an effort to change the culture of instructionist teaching in the school, we introduced the AR Sandbox to the boarding academy, co-designing and supporting collaborative activities that the teacher primarily facilitated. The academy provided a dedicated room, which we populated with four AR Sandboxes, each with a white board cover and monitor (Fig. 3). The white board cover was used at times to give groups the opportunity to draw and share their ideas collaboratively and for particular activities such as when they were asked to envision and draw a cross-sectional view of a landscape; the monitors were used to both orchestrate learning activities and display 2D representations of what was shown on the sand.

For this study, we co-designed a curriculum to extend over seven 1.5 h workshop sessions based on the same introductory topographical topics as were previously taught. Forty-two students (separated into 2 sub-groups of 21 students each that met independently) participated, such that each workshop occurred twice. We worked carefully with the teacher to repurpose these activities so the students could explore the ideas on the AR Sandbox with the support of their peers. Meetings started with discussions about knowledge building principles such as improvable ideas, democratizing knowledge, idea diversity, and symmetric knowledge advances (Zhang et al. 2011). Following this, students engaged in various types of small group activities around the AR Sandboxes, facilitated by a set of increasingly complex activities that were posted on each monitor. This allowed the groups to work at their own pace with minimal guidance by the instructor, only as needed. The instructor's role was to walk around, periodically ask or answer questions from the students, and in general to scaffold deeper inquiry when the instructor observed that the students needed it. At times, cross-group activities were designed. For example, the second and third meetings were two parts of a Jigsaw activity. During the first part, expert groups focused on one particular topographical concept; during the second part, groups were mixed with each expert teaching the other participants what they knew (Şengül and Katranci 2014; Berger and Hänze 2016).

After the activities on the AR Sandbox, whole group discussions were carried out. These generally included reflection questions about students' collaborative experiences, opportunities to share what and how they learned as well as their open questions, student-led discussions where they shared their alternative conceptions on the topographical concepts they explored, and suggestions for future activities that would help them go deeper.

Data collection and analysis

To examine DSS using the AR Sandbox, we collected audio and video recordings of the full seven meetings. Data were collected using small, 360 degree cameras that were mounted on each AR Sandbox, allowing us to capture all activities on the sand vis-a-vis the monitor. In

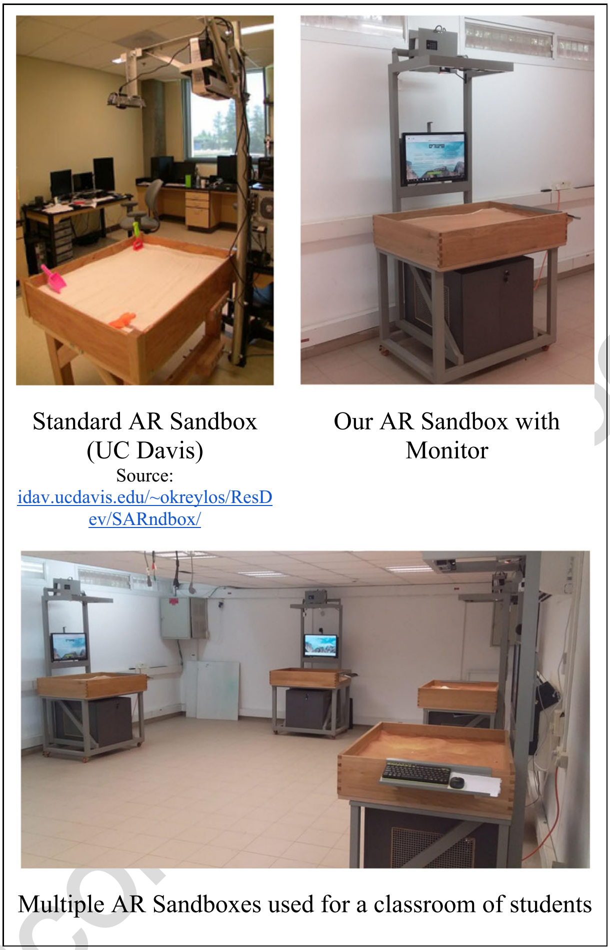
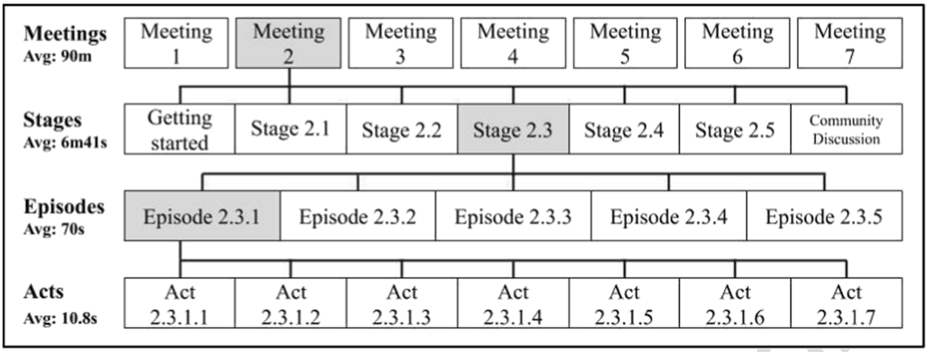


Fig. 3. Picture of general AR Sandbox and our design showing the monitor, as well as a picture of the classroom showing several of them

total, this included 19 h and 37 min of video data collected from AR Sandbox activities across all the different groups during the seven meetings. The use of the 360 degree cameras allowed the students to habituate to the camera quickly, as they were not operated by humans and were positioned above the monitors in a location that did not stand out.

Our approach involved two parallel processes that allowed us to elucidate progressively finer levels of the participants' shared meaning making in coordination with their resources, until we reached a saturation point. One process that took place was reviewing the entire data corpus and segmenting it to ethnographic chunks where there were clear beginnings and endings. Ethnographic chunks are small, identifiable behavioral units taken from larger events of coherent, meaningful interactions. An ethnographic chunk, for example, may include the giving of advice as part of the event of a medical consultation (Jordan and Henderson 1995).

Due to the scope of the data, ultimately we created a taxonomy that included stages (events), episodes (our ethnographic chunks), and DSS acts (chunk sub-divisions) to catalogue and classify the seven AR Sandbox meetings (Fig. 4). First, we divided meetings into stages



Q1 **Fig. 4.** Segmentation of activities with example sub-divisions and mean duration

every time there was a clear beginning and ending of a particular task in relation to the students' goals and the tool. For example, one stage in a particular meeting involved the students engaging in a task where they examined a cross-sectional representation of a mountain range that was posted on the monitor. In the subsequent stage, they worked together to represent the map on the sand. In the stage after that, they began drawing the mountain range as a 2D map on the whiteboard. After we identified the stages, we subdivided these into episodes that were based on specific ideas or questions that the groups pursued. For example, when they were drawing the mountains on a whiteboard in the stage described above, the first episode involved them deciding which mountain range to explore. In the subsequent episode, they debated how this should be represented. Lastly, we further subdivided the episodes into acts based on the type of spatial thinking that was involved. This level of analysis is reported in our findings.

The second parallel analysis process that we engaged in started with the creation of content logs after each meeting where we recorded the overall significance of events as well as any focal activities or "hot spots" (Jordan and Henderson 1995) where the unique affordances of the AR Sandbox was evident and included multiple modalities. This allowed us to dive deeply into several of the activities, based on transcriptions, to inductively find the categories that were relevant. We ended up iteratively developing a representational system, what we refer to as *constellations*, that included chronological accounts showing the way spatial thinking was distributed across the material, social, and activity contexts. The constellations corresponded to verbal and non-verbal forms of communication that we captured in images of the students working on the sand in conjunction with transcriptions of their talk. Developing these representations was necessary to accurately capture DSS at a micro-analytic level and interpret the ongoing learning in-situ (Chinn and Sherin 2014).

In this article, we report on DSS acts that occurred within two respective episodes that took place during different stages within the second meeting. We chose these episodes in part due to their typicality and representativeness (Yin 1994). By representativeness we mean the extent that the episodes highlighted important aspects of the DSS process; and by typicality we mean the extent to which the processes occurred in ways that were common to the larger population. In addition to making our case to readers about the necessity and appropriateness of the representational tools that we developed, we chose these particular episodes because they provide contrasting accounts of DSS with and without the unique affordances of the AR. That is, the first episode occurred within the first stage of the second meeting where students were asked to explore a topographical concept on the sand *without* the AR features. After turning on the AR 4 min and 39 s after the first episode and getting oriented for the first time (for the next 6 min and 29 s), they then returned to explore similar ideas on the same topic, this time using the AR features. Having these two episodes in near proximity allowed us to more carefully examine the affordances of the AR and the way spatial thinking was distributed across this material context.

Distributed spatial Sensemaking on the AR sandbox

The current analysis focuses on a 35-min activity during the second meeting when groups worked mostly without the direction of the teacher on several challenges posed in the AR Sandbox curriculum. This involved having small groups of students explore one of four different topographical features (i.e., hilltop, ravine, saddle, ridge) first on the 2D map then on the AR Sandbox. This was in preparation for the third meeting where one expert from each group met in jigsaw groups to share their knowledge. The current analysis focuses on the ravine group, which included Tom, Zed, Uri, Sue, and Pat (pseudonyms). We divided their entire 35 min activities on the sandbox into five stages. For the Interaction Analysis, we focused on one 69-s episode during Stage 1, and a second 71-s episode during Stage 3 (Fig. 5).

Coordinating resources for distributed spatial sensemaking

The unique affordances of the AR Sandbox created "a social field within which certain activities become very likely, others possible, and still others very improbable or impossible" (Jordan and Henderson 1995, p.75). Our Interaction Analysis of two episodes (one with and one without the AR features) in close temporal proximity and with the same students provided us with an opportunity to shed light on how collaboration played out across the AR Sandbox. We found that the AR contour lines and water on both the sand and the accompanying monitor were highly consequential resources that groups needed to coordinate as part of their DSS.

During the first episode, students worked on the sand (without the AR), but saw a corresponding 2D map on the monitor. We found that the students' DSS was distributed across a number of resources including the map on the monitor and the artifacts on the sand that the students acted on and examined. For example, during act 1A, the students engaged in extrinsic static spatial thinking that came across through their spatial talk and three instances of

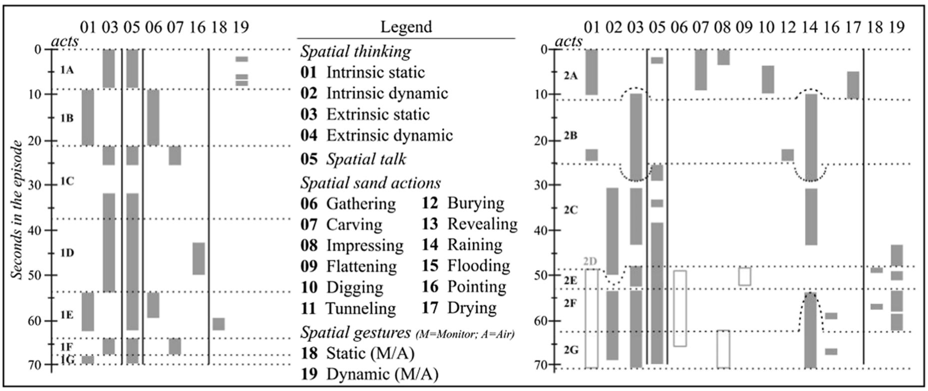


Fig. 5. Left: Episode 01 Constellations (without AR); Right: Episode 02 constellations (with AR)

meaningful dynamic spatial gestures. The following interactions took place, illustrated in Fig. 6.

Act 1A.

Time	#	Person	Expression	DSS[3]
00:00	19	Pat	Isn't a ravine connected to water?	03, 05
00:01–00:02	20	Tom	In principle water flows down from there [ravines]	03, 05
00:02–00:03	21	Zed	Here is where the water falls [i1: points on the screen in the downwards direction that the water flows within the ravine][4]	03, 05, 19
00:04	22	Tom	Yes, this…	
00:05–00:06	23	Zed	...this is where the water falls [i2-i3: makes a lowering motion in the air to represent the direction of falling water]	03, 05, 19
00:06–00:07	24	Tom	Think! Where there is rain on top, that is where is goes down [i4: Zed lifts his hand again]	03, 05, 19
00:07–00:08	25	Zed	Yes, where the rain falls down [i5: lowers his hand and looks at his peers to see if they understand what he explained].	03, 05, 19

Pat's question (19)[5] initiated a conversation around the gravitational idea of falling water (20–25). Zed first used his index finger to show the scope of the ravine on the monitor, and after that made a hand motion demonstrating the descent of water, which he also explained (21). At this point, Tom made the rule-of-thumb that when water is on top, it always flows down the ravine (24). Acting as a distributed assistant, Zed repeated his hand motion again, this time looking at his peers to see if they understood Tom (25).

The spatial thinking demonstrated in this act was extrinsic static [03][6] because it involved the relations between two objects, in this case being the top and the bottom of the hill, connected by flowing water based on gravitational pull. This was expressed through spatial talk relating to the water actions on the ravine. There were no actions on the sand, but the use of gestures in the air and on the monitor [18] expressed this type of spatial thinking.

In a subsequent act (1E), the students tried to define ravines and identify them on the map with the help of the sand. This act began when Zed called over the teacher after another group member (Tom) distinguished between the ravine as an object of water with their new understanding that the ravine played a function in water flow (by being a draining system).

Act 1E.

Time	#	Person	Expression	DSS
00:54–00:58	33	Zed	[waiving the instructor over and talking simultaneously] If I define ravine, from what I understood from the map, we can say it is a mountain	01, 05
00:54–00:58	34	Zed	[i10: Gathers sand to make a hill]	01, 06
00:59	35	Ins.	[restating Zed's point] This is a ravine? [i11: Points to the ravine on the monitor]	01, 05-,18
00:60	36	Zed	Yes	
00:60–00:63	37	Pat	Both of these are ravines [i12: Points to the monitor]. They [the assignment] defined two ravines for us.	01, 05-,18

[3] Refers to the DSS types in the constellation tables (Figure 5).

[4] Square brackets with number preceded with an "i" refer to the illustration in the accompanying figure.

[5] Parentheses refer to the line number of the expression in the accompanying act.

[6] Square brackets within text refer to the type of spatial thinking listed in the accompanying act and illustrated in the constellation tables (Figure 5).

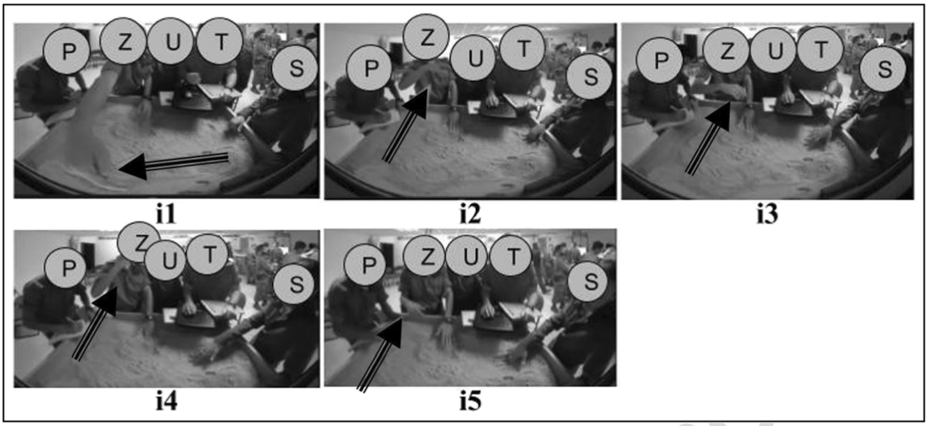


Fig. 6. i1-i5

Zed's point about a ravine being a mountain (33), which he gathered on the sand (34) and which the instructor (35) and Pat (37) pointed to on the monitor, showed that the group corrected the interpretation they had earlier about a ravine being the water. This statement, dealing with the features of the topography, involved spatial thinking that was intrinsic static [01] because it distinguished an object from others (Fig. 7).

Across both of these acts, the students would have had to imagine the contour lines on the sand, communicate their different understandings to the other members of the group, and reach some sort of agreement. The lack of the water function could have behaved similarly as contour lines. It would have required the students to imagine the directionality of the water flow and potentially lead to different interpretations about the structure of the ravine. Based on the absence of these AR functions, we accordingly only found spatial thinking that was intrinsic and extrinsic static during this episode.

By the second episode, with the contour lines and water functions of the AR turned on, there were more sand actions and spatial gestures exhibited, leading to a new form of spatial thinking. Specifically, during act 2C, the students engaged in a discussion focused on understanding the 2D representation of the 3D sand they were manipulating.

Act 2C.

Time	#	Person	Expression	DSS
00:31–00:43	17	Tom	[i7: Looks at the monitor and simultaneously raises his hand above the hill to make it rain]	02, 03, 14
00:34–00:35	18	Zed	[looking at the monitor] Through the ravine.	02, 03, 05
00:38–00:41	19	Tom	Yes, it is possible to see two [ravines] and it [the water] goes down to the left in an unclear way	02, 03, 05
00:42–00:45	20	Zed	Pay attention that here there is a pointing finger like he [the instructor] said [referring to the instructor's heuristic in Stage 1 where he points out that ravines look like fingers on the 2D map]. [i8: moves his hand back and forth on the monitor to point out how the ravine looks like a finger in its 2D representation]. So it is like	02, 05, 19
00:44	21	Pat	A ravine	02, 05
00:46–00:47	22	Zed	So, like, pay attention [i9: Again moves his hand to show the ravine on the monitor, this time a little more accurately]	02, 05, 19
00:48–00:49	23	Pat	Here [i10: Points to the same ravine on the monitor]	02, 05, 18

Fig. 7. i10-i12

Tom's response of moving his hand to the saddle to make it rain (17), as he looked simultaneously at the monitor, suggested that he was looking for new insights from the 2D representation on the monitor. Zed's answer that it was the ravine (18) occurred in parallel, irrespective of Tom's act, apparently understanding the relationship between the ravine and water flow differently. Still, Zed and the other group members followed along with Tom's act, particularly when he provided an explanation about the direction of the ravine going to the "left" and "down" (19). These expressions included two types of spatial thinking. They included extrinsic static spatial thinking because they related to the positionality of the water relative to the hill as well as to the gravitational pull on the water; They included intrinsic dynamic spatial thinking because they examined the correspondence between the sand and the map. Zed's follow up (20), with both a comment and dynamic gesture on the monitor, referred to an earlier discussion when the instructor provided a heuristic that ravines looked like fingers pointing in a certain direction. This was intrinsic dynamic because he referred to the sand-map correspondence. After Pat identified it as the ravine, apparently thinking out loud (21), Zed repeated his own words and gestures (22). Pat's final static pointing to the same ravine on the monitor (23) reinforced Zed's identification of it (Fig. 8).

On the whole, this was the first act where the students made explicit connections between features on the sand with those that were on the 2D map. While they had in the past used the sand to examine the map (Act 1E), with the AR features turned off there was no easy way for

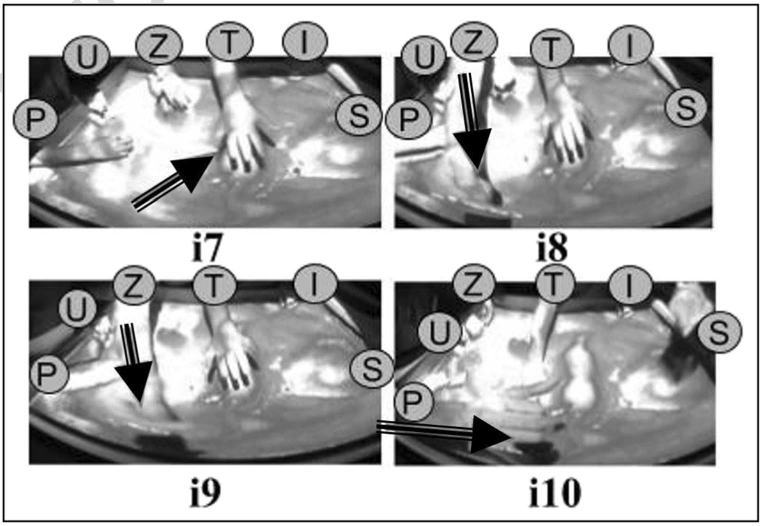


Fig. 8. i7-i10

them to know if the two corresponded. With the AR features on, the map and the projection on the sand were replicas of one another, allowing them to get the feedback to determine if their interpretations were correct. In this particular act, they now tentatively made the connection between how the topography looked in its 2D representation with its 3D representation on the sand.

It took the group about 30 s to exhibit intrinsic dynamic spatial thinking. This first occurred when Zed, responding to Tom's attempt to make it rain while looking at the monitor, moved his finger along the ravine on the sand to show the correspondence between the sand and 2D map regarding the directionality of the ravine. He expressed this as a rule-of-thumb about the contour lines looking like a finger. Zed's explanation scaffolded Sue's query, as she now apparently understood there was a correspondence between the lines and the ravine's directionality, but was not sure what it was. This ultimately led to a very sophisticated discussion where the group made rich connections, mainly focused on the 2D representation on the monitor, but clearly in relation to their activities on the sand. Ultimately, the group was able to accomplish the challenging goal of connecting between 2D and 3D representations in this short amount of time.

To sum up, during the first episode, two types of spatial thinking were expressed along with only a few sand manipulations and gestures. Overall, the group was not able to make accurate connections between the 2D and 3D representations. We believe the absence of the unique affordances of the AR contour lines and water made it unlikely for them to accomplish these goals, particularly without guidance. The second episode substantiates our contention, since while having these affordances the group very quickly accomplished this goal. It was the unique synergy between the different affordances that appeared to have supported the intrinsic dynamic spatial thinking required to do this. Additionally, the use of the monitor was consequential because it provided the group with both representations and therefore allowed them to discover, on their own, their correspondence.

Intricacy and Speed of Trouble and Repair with AR.

Another feature of the interaction that was evident from our data was the way small groups "draw on their bodily, artifactual, spatial, and social resources to mend infraction of projected sequences" (Jordan and Henderson 1995, p. 70). A telling example of the way activities can be broken and quickly repaired can be seen in the second episode in acts 2E and 2F. In act 2E, Sue asked the group a question about where ravines begin and end that stopped the progression of the group as they sought to address her.

Act 2E.

Time	#	Person	Expression	DSS
00:49–00:51	28	Sue	Now, the ravine is in this downwards direction? [i11: Moving her finger in the direction of the ravine] or to here? [i12: Moving her finger in a different direction]	03, 05, 19
00:51	29	Pat	[i13: Moves his finger in both directions on the sand]	03, 19

Specifically, Sue's question was extrinsic static because she asked about the directionality of the ravine (28). In response, the group made a discovery through their spatial talk that connected between the AR Sandbox and the real-time 2D representation on the monitor, expressed through what elevation looks like in addition to the structure of ravines on the 2D map. Having the monitor mirror what is created on the AR Sandbox afforded quick repair and advancement of spatial thinking, as shown in the following transcript:

Act 2F.

Time	#	Person	Expression	DSS
00:53–00:54	30	Zed	Yes, what is the question? [all the group members look at the screen]	
00:54–00:55	31	Pat	From here, to there [i14: moves his finger from the middle of the screen to his right on the screen, showing the direction that the ravine goes down]	02, 03, 05, 19
00:54–00:55	32	Sue	The ravine, is it like this? [i15: points from the middle of the screen to the beginning of the ravine at the top of the hill]	02, 03, 05, 19
00:56–00:57	33	Sue	It goes from here to there? [i16: moves her finger in the same way as Pat]	02, 03, 05, 19
00:57–00:58	34	Pat	Yes, from here it is higher [i17: moves his finger with the same gesture as before]	02, 03, 05, 19
00:56–00:58	35	Zed	It falls, you [referring to Sue] didn't notice here	02, 03, 05
00:58–00:59	36	Zed	[i18–19: Puts his finger on the top of the ravine on the sand and moves it along the ravine until the bottom, at the same time looking at the monitor which picked up his hand motion]	02, 03, 16
00:59–00:62	37	Pat	From the top [i20: Points his finger to the top of the ravine on the monitor that Zed's finger was currently showing] to the bottom [i21: Moves his finger to the bottom-most part of the ravine before moving it back to the top]	02, 03, 05, 19

Zed's entering the conversation (from doing something else) to try and understand what Sue was asking (30) marked the beginning of the repair. Pat then provided an answer to Sue (31), but was interrupted by her when she clarified the question while moving her finger along the ravine on the monitor. She first did this in one direction, from bottom to top (32), then from the top to bottom (33), suggesting that on the map (monitor) the elevations were not clear to her. Pat, apparently understanding Sue's confusion on the elevations, then clarified where the top of the hill was on the monitor to identify the directionality of the ravine (34). Zed reinforced this point with the word "falls" (35), again suggesting that Sue needed to understand the elevation. In parallel, Zed showed this by moving his finger on the sand, which showed up on the monitor where everyone was looking (36). With this motion, Zed took advantage of a unique affordance of the AR Sandbox and monitor to combine both the 3D and 2D representations. By tracing the motion on the monitor that Zed carried out on the sand, Pat further emphasized how to see elevation on the 2D representation (37) (Fig. 9 and Fig. 10). Q2

To sum up, during the 13 s period that followed Sue's question, the group moved from a position of trouble to one where they quickly repaired the break. The sequence included a question and simultaneous dynamic gesture on the monitor, followed by a gesture in the air, a verbal clarification, a gesture on the monitor, a question and gesture on the monitor, another

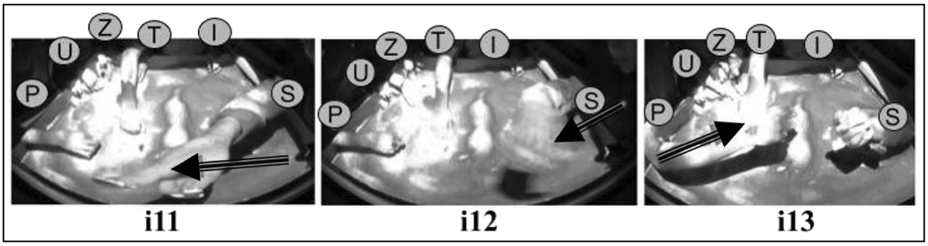


Fig. 9. i11-i13

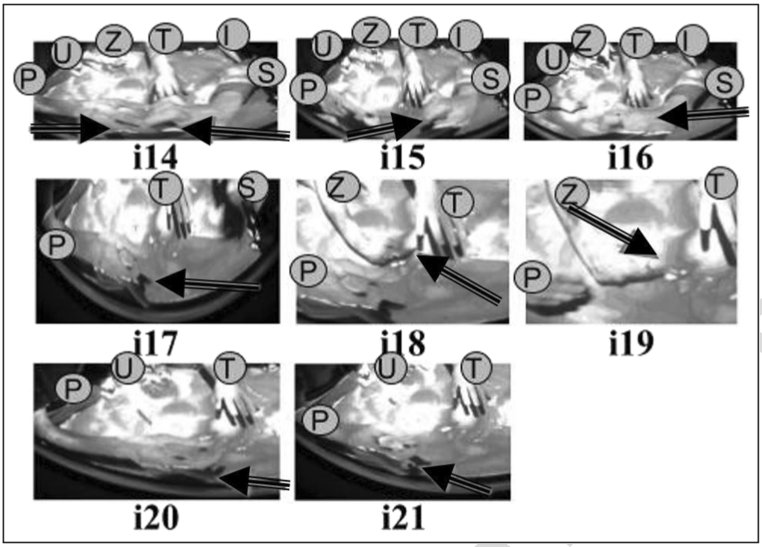


Fig. 10. i14-i21

gesture on the monitor, an explanation and gesture on the sand, and finally a corresponding gesture on the monitor. This sequence, taking advantage of available material and social resources on the AR Sandbox, showed both the multimodal intricacy and fast-pace involved when groups face misalignments or misunderstandings that need to be repaired.

Semi-divergent and convergent turn-taking with AR

One of the ways that spatial thinking evolves is through turn-taking, an emergent interactional exchange system that includes the participants and the instruments they use (Jordan and Henderson 1995). A key affordance of the AR Sandbox is its size and multi-touch capabilities. This allows the different group members to try solving the same or disparate problems using divergent, semi-divergent, and convergent instrumentation.

An example of divergent instrumentation occurred in act 2D, which we visualized as hollow rectangles in Fig. 5 (right) to denote that they were peripheral acts to the central DSS process. Specifically, Uri was trying to make it rain and improve the hill that he created near him on the sand, while Tom was flattening an area near the hill instead. While their explorations had spatial meaning, they were not connected in any observable way to the central group discourse and thus we consider them divergent.

Act 2D.

Time	#	Person	Expression	DSS
00:47–00:48	24	Uri	Why doesn't water fall for me?	
00:48–00:52	25	Tom	[Flattens the area near the hill]	01, 09
00:48–00:66	26	Uri	[Gathers sand to the existing hill he created]	01, 06
00:67–00:71	27	Uri	[Impresses the sand on the hill]	01, 08

Semi-divergent instrumentation can be seen in the second episode in act 2B, when the group tried to add augmented water and use its properties to examine the topography they created. This is an illustration of the unique functionality and use of the AR Sandbox, which allows topographical theories or conjectures to be tested.

Act 2B.

Time	#	Person	Expression	DSS
00:10–00:29	10	Pat	[i4: Raises his hand above the hill to make it rain]	03,
14				
00:11–0:28	11	Uri	[i4: Tries to make it rain by spreading his fingers]	03,
14				
00:16	12	Zed	Do it like this [i4: Opens fingers to demonstrate]	03,
14				
00:17–0:18	13	Uri	Why isn't it [rain] coming down? Ah here it falls [i5: He successfully produces rain using his hand]	03,
14				
00:19–0:20	14	Pat	[i5: Tries again to make it rain while looking at the monitor to see if it appears there too]. Where is the rain? Stop pressing [referring to Sue pressing the button to make it dry].	03,
14				
00:22–0:23	15	Uri	No, don't press.	
00:22–0:24	16	Sue	[i6: Buries the water in the hole with sand]	01,
12				

The semi-divergence can be seen when Pat and Zed were independently trying to make it rain on different parts of the ridgeline, while Sue was digging a hole to create a drainage basin for the water along her side of the table. Specifically, the act of making it rain involved extrinsic static spatial thinking. This is because it involved an understanding of gravitational force that pulls water downwards, to the lowest point. The rain that Pat managed to activate on the AR Sandbox (10–14) led the water to flow in three directions, primarily along the three ravines on the hill that Pat created (Fig. 11). This provided Sue with the opportunity to test an earlier insight that she made about how it turned blue when she dug holes, as if she reached groundwater. While significant sensemaking did not take place during this 14 s act, the activity on the sand and the spatial thinking involved was a meaningful test of the group's effort to understand how water flows within ravines. Although the students were engaged in different activities on the sand, they were coordinated by a shared, central discourse focused on making sense of ravine features.

At times, these semi-divergent activities converged, particularly when some insight was made or a promising direction was found. We see this clearly in act 2C (above) with an act of teacher noticing (Schack et al. 2017) of semi-divergent activity and an intervention. Consequently, the instrumented interaction immediately converged around a central ridgeline in the AR Sandbox that the group worked on earlier. In act 2E (above), we found another

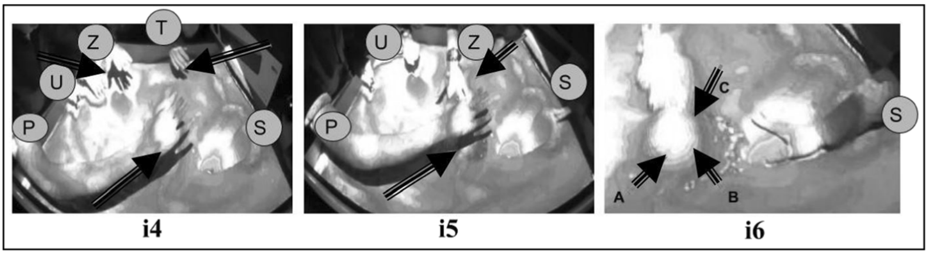


Fig. 11. i4-i6

convergence, this time initiated by a student (Sue) when she interrupted the flow of the group with a question that they collectively responded to.

Discussion and conclusions

This study aimed to examine how spatial thinking takes place when collaborative groups use the AR Sandbox to study topography. It is already well accepted that learning is mediated by sociomaterial resources (Vygotsky 1978). Still, understanding their specific roles to support learning is an important goal of research in STEM generally (Bricker and Bell 2014) and CSCL specifically. Our findings show different ways that features of the AR Sandbox support the spatial thinking of groups.

Our first finding extends Ramey and Uttal's (2017) claim that the type of activity influences DSS in what we see as an instantiation of what Enyedy et al. (2015) describe in their liminal blends framework. Specifically, this finding showed how the specific AR features of projected contour lines and water on sand in parallel to their 2D representation on a monitor required coordination and led to more challenging or advanced accomplishments. While we can imagine that the intrinsic dynamic spatial thinking that took place could occur without these AR features, there would be substantial difficulties in expressing this spatial thinking. Potentially, with proper mediation, the group could have achieved this. For example, had they more time, one of the participants could have tried to imagine the contour lines on the sand and connected them to the representation on the monitor. Alternatively, this could have been introduced to the group by the instructor. The fact that the episodes did not unfold this way in the first episode without the AR features, nevertheless, suggests that the material resources (of the AR) raised the likelihood for the group to engage in the type of spatial thinking that was useful for them to coordinate between 2D and 3D topographical representations. The episodes we analyzed were an instantiation of liminal blends (Enyedy et al. 2015) because they showed how the spatial thinking required coupling with the material resources (namely the AR features) and how this, over time, led the group to see the relevance of the monitor, using it to advance the way they were making sense of the ravine's directionality. This finding extends our understanding of the situated nature of sensemaking, and particularly how it is distributed across material and social contexts. It provides micro-level evidence supporting the notion that spatial thinking is contextualized and malleable (Uttal et al. 2013), since without the material context of the AR affordances, the group did not achieve the intrinsic dynamic spatial thinking that they did with the AR features.

The second finding showed the fast way that trouble and repair occurred, within just a few seconds, allowing the group to reorganize towards future and more sophisticated DSS activities (Rogoff 1995). Our interpretation of the events widen Ramey and Uttal's (2017) notion of the activity context, which we believe is multi-layered. Specifically, acts 2E and 2F highlighted some of the unspoken rules by which the activity sphere was organized (Jordan and Henderson 1995). We believe that, at least in part, the hidden social mechanisms can be found in the activity context, which was embedded in the authenticity of the task. Lyons (2018) Q3 describes how AR often simulates authenticity by creating representations of phenomena that are practiced by professionals. As described in the setting of this research, the entire study of topography within the academy was in preparation for a navigational exercise that students needed to complete in the field. This specific boarding academy had the aims of preparing these students to eventually be officers in the army. The culture of not leaving anyone behind and being responsible towards others was ingrained in the institution, particularly as army life often involved life and death situations. Therefore, as the group moved forward on the AR activity, one of its hidden social concerns was to ensure that no individual learner fell behind. While we can only conjecture as to the underlying reasons that the trouble and repair occurred so quickly, the fact that the group realized there was trouble, stopped certain in progress activities, and invested a great deal of their available resources to move forward, suggests that the activity context played an important role in their DSS, in interaction with the affordances of the AR Sandbox. Exploring the multiple layers of activity contexts opens new questions about how to examine the hidden aspects of social organization, as well as how to foster successful forms of DSS, as the group in question achieved.

Lastly, the AR Sandbox has a number of specific affordances that shape the DSS in intricate ways. Specifically, the size and multi-touch capabilities of the sandbox afforded the opportunity for five students to work divergently, semi-divergently, and convergently over different acts to productively advance their DSS. While we are not in a position to make any value judgements as to which combinations of these different approaches are most productive, our findings do suggest that allowing for all the different participants to explore the AR features simultaneously was an important facet of their progress. Allowing for the ebb and flow of collaboration to occur without over-scripting appeared to open opportunities for meaningful shared sensemaking (Dillenbourg 2002). Stated differently, our findings show that beyond there being opportunities for divergent, semi-divergent, and convergent activity, the seamless transitions between them appear to allow the group to continuously address the most advanced or emergent questions or issues that arise.

Implications and next steps

With the creation of constellations, we have developed a new methodological tool to examine how groups explore basic topographical features using the AR Sandbox. This provides a way to parse highly complex, distributed interactions into fine-grained units that can be understood and can help trace the advancement of DSS. This methodology can be widened at a local level to examine all sorts of topographical features and activities to shed light on the way topographical learning occurs in our setting, and in a more general level may be applicable to analyses with other distributed activities using AR.

On a practical level, the examination of the way DSS occurs in groups can be useful for AR Sandbox aficionados and researchers around the world. AR Sandboxes are frequently found within museums, providing visitors with an opportunity to play and be impressed with their technological capabilities. We are not surprised, however, that the few studies on learning (and not perceptions of it) with the AR Sandbox have not demonstrated significant results (e.g., Giorgis et al. 2017). We believe that this is both because of the coarse level of granularity that those studies have adopted, and the lack of scaffolding provided to the learners (socially, materially, and culturally).

Lastly, and unexpectedly, the monitor that we added to the system (originally for the purposes of orchestrating activities) became highly consequential for the students, showing us the importance of having a flat 2D representation alongside the 3D representation on the sand. As far as we know, no other AR Sandbox design has a monitor showing the 2D representation alongside the projection on the sand. The fact that the students went to the monitor without prompting suggests that having a separate, 2D-only representation, supported their ability to make sense of the 3D version. Our research suggests that having both representations alongside one another is more effective at advancing DSS than just the AR Sandbox alone. This is a logical apparatus for topographical study and is ultimately a valuable tool for people to be able to competently interpret 2D topographical maps. AR Sandbox aficionados and researchers should consider this in their future designs.

Conclusion

Our study focuses on moment-to-moment interaction in real-time to understand the coordination involved in the complex activities involved in DSS using the AR Sandbox to study topography. Our findings show how significant accomplishments, which may often seem subtle or irrelevant without careful investigation, occur within timeframes that are often just seconds long. Understanding learning processes at this granularity is significant for the class of dialogic studies interested in the AR Sandbox and CSCL more generally. As we have shown in our review, existing scholarship on the AR Sandbox may be taking too coarse a view, potentially missing the real benefits of this device. Using Interaction Analysis, the results of this study point to the intricate ways that the AR Sandbox can support learners when they are thoughtfully considered in the design. AR is an emerging and exciting area of scholarship in CSCL, opening up new opportunities to enrich the way people learn in today's society.

References

Alibali, M. W., & Nathan, M. J. (2007). Teachers' gestures as a means of scaffolding students' understanding: Evidence from an early algebra lesson. In R. Goldman, R. Pea, B. J. Barron, & S. Derry (Eds.), *Video research in the learning sciences* (pp. 349–365). Mahwah, NJ: Erlbaum.

Arnseth, H. C., & Ludvigsen, S. (2006). Approaching institutional contexts: Systemic versus dialogic research in CSCL. *International Journal of Computer-Supported Collaborative Learning, 1*(2), 167–185.

Bakhtin, M. M. (1986). *Speech genres and other late essays* (VW McGee, trans.; C. Emerson & M. Holquist, Eds.). Austin, TX: University of Texas Press. (Original work published 1979).

Bandrova, T., Kouteva, M., Pashova, L., Savova, D., & Marinova, S. (2015). Conceptual framework for educational disaster center "save the children life". *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 40*(3), 225–234.

Berger, R., & Hänze, M. (2016). The jigsaw method in 12th-grade physics classes–impact of the group's ability composition on academic performance. *International Journal of Modern Education Research, 3*(5), 28–36.

Bricker, L. A., & Bell, P. (2014). "What comes to mind when you think of science? The perfumery!": Documenting science-related cultural learning pathways across contexts and timescales. *Journal of Research in Science Teaching, 51*(3), 260–285.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32–42.

Carbonell, C., & C., & Asensio, L. A. B. (2017). Augmented reality as a digital teaching environment to develop spatial thinking. *Cartography and Geographic Information Science, 44*(3), 259–270.

Chinn, C. A., & Sherin, B. L. (2014). Microgenetic methods. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed., pp. 171–190). New York, NY: Cambridge University Press.

Coburn, C. E., & Penuel, W. R. (2016). Research–practice partnerships in education: Outcomes, dynamics, and open questions. *Educational Researcher, 45*(1), 48–54.

Cuendet, S., Bonnard, Q., Do-Lenh, S., & Dillenbourg, P. (2013). Designing augmented reality for the classroom. *Computers & Education, 68*, 557–569.

Danish, J. A., DeLiema, D., & Enydey, N. (2015). Constructing liminal blends in a collaborative augmented-reality learning environment. *International Journal of Computer-Supported Collaborative Learning, 10*(1), 7–34.

Darley, N. T., Tavares, T. A., Costa, V., Collares, G., & Terra, V. (2017). Tangible interfaces: An analysis of user experience using the AR sandbox project. In *Proceedings of the XVI Brazilian Symposium on Human Factors in Computing Systems* (p. 65). ACM.

Dillenbourg, P. (2002). Overscripting CSCL: The risks of blending collaborative learning with instructional design. In P. A. Kirschner (Ed.), *Three worlds of CSCL. Can we support CSCL?* (pp. 61–91). Netherlands: Open University.

Enyedy, N., Danish, J. A., Delacruz, G., & Kumar, M. (2012). Learning physics through play in an augmented reality environment. *International Journal of Computer-Supported Collaborative Learning, 7*(3), 347–378.

Enyedy, N., Danish, J. A., & DeLiema, D. (2015). Constructing liminal blends in a collaborative augmented-reality learning environment. *International Journal of Computer-Supported Collaborative Learning, 10*(1), 7–34.

Evans, M., Fleming, B., Thwala, Z., & Drennan, G. (2018). Can the augmented reality sandbox help learners overcome difficulties with 3-D visualization? *Terrae Didática, 14*(4), 389–394.

Florinsky, I. (2016). *Digital terrain analysis in soil science and geology.* Amsterdam, NE: Elsevier Academic Press.

Giorgis, S., Mahlen, N., & Anne, K. (2017). Instructor-led approach to integrating an augmented reality sandbox into a large-enrollment introductory geoscience course for non-majors produces no gains. *Journal of Geoscience Education, 65*(3), 283–291.

Goldin-Meadow, S., Levine, S. C., Zinchenko, E., Yip, T. K., Hemani, N., & Factor, L. (2012). Doing gesture promotes learning a mental transformation task better than seeing gesture. *Developmental Science, 15*(6), 876–884.

Hod, Y., & Sagy, O. (2019). Conceptualizing the designs of authentic computer-supported collaborative learning environments in schools. *International Journal of Computer-Supported Collaborative Learning, 14*(2), 143–164.

Ishii, H. (2008). The tangible user interface and its evolution. *Communications of the ACM, 51*(6), 32–36.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *The Journal of the Learning Sciences, 4*(1), 39–103.

Keifert, D., & Stevens, R. (2019). Inquiry as a members' phenomenon: Young children as competent inquirers. *Journal of the Learning Sciences, 28*(2), 240–278.

Koschmann, T. (2018). Ethnomethodology; studying the practical achievement of intersubjectivity. In F. Fischer, C.E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.). *International Handbook of the Learning Sciences* (pp. 465–474). Routledge.

Kreylos, O. (2016). *Augmented Reality Sandbox*. Retrieved from the Institute for Data Analysis and Visualization (IDAV).

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge, UK: Cambridge University Press.

Markoski, B. (2018). *Basic principles of topography.* Cham, Switzerland: Springer Geography.

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In J. S. Gero (Ed.), *Studying visual and spatial reasoning for design creativity* (pp. 179–192). New York, NY: Springer.

Pruden, S. M., Levine, S. C., & Huttenlocher, J. (2011). Children's spatial thinking: Does talk about the spatial world matter? *Developmental Science, 14*(6), 1417–1430.

Ramey, K. E., & Uttal, D. H. (2017). Making sense of space: Distributed spatial sensemaking in a middle school summer engineering camp. *Journal of the Learning Sciences, 26*(2), 277–319.

Reed, S. E., Kreylos, O., Hsi, S., Kellogg, L. H., Schladow, G., Yikilmaz, M. B., & Sato, E. (2014). Shaping watersheds exhibit: An interactive, augmented reality sandbox for advancing earth science education. *AGU Fall Meeting Abstracts, 1*, 1–29.

Richardson, R., Sammons, D., & Delparte, D. (2018). Augmented affordances support learning: Comparing the instructional effects of the augmented reality sandbox and conventional maps to teach topographic map skills. *Journal of Interactive Learning Research, 29*(2), 231–248.

Rogoff, B. (1995). Observing sociocultural activity on three planes: Participatory appropriation, guided participation, and apprenticeship. In J. V. Wertsch, P. D. Rio, & A. Alvarez (Eds.), *Sociocultural studies of mind* (pp. 139–164). Cambridge, UK: Cambridge University Press.

Rogoff, B., & Chavajay, P. (1995). What's become of research on the cultural basis of cognitive development? *American Psychologist, 50*(10), 859.

Sánchez, S. Á., Martín, L. D., Gimeno-González, M. Á., Martín-Garcia, T., Almaraz-Menéndez, F., & Ruiz, C. (2016). Augmented reality sandbox: A platform for educative experiences. In *Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality* (pp. 599-602). ACM.

Sawyer, R. K. (2014). Foundations of the learning sciences. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed., pp. 1–20). New York, NY: Cambridge University Press.

Schack, E. O., Fisher, M. H., & Wilhelm, J. A. (Eds.). (2017). Teacher noticing: Bridging and broadening perspectives, contexts, and frameworks. Cham: Switzerland: Springer.

Şengül, S., & Katranci, Y. (2014). Effects of jigsaw technique on mathematics self-efficacy perceptions of seventh grade primary school students. *Procedia - Social and Behavioral Sciences, 116*, 333–338.

Stahl, G. (2012). Theories of CSCL. In J. Haake, G. Schwabe, & M. Wessner (Eds.), *CSCL-kompendium 2.0* (pp. 16–30). Frankfurt, Germany: Oldenburg.

Stahl, G., Koschmann, T., & Suthers, D. (2006). Computer-supported collaborative learning: A historical perspective. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 409–426). New York, NY: Cambridge University Press.

Steinhardt, L. (1998). Sand, water, and universal form in sand play and art therapy. *Art Therapy, 15*(4), 252–260.

The National Research Council. (2006). *Learning to think spatially: GIS as a support system in the K-12 curriculum*. Washington DC: National Academies Press.

The National Research Council. (2009). *Learning science in informal environments: People, places, and pursuits*. Washington, DC: The National Academies Press.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352–402.

Vaughan, K. L., Vaughan, R. E., & Seeley, J. M. (2017). Experiential learning in soil science: Use of an augmented reality sandbox. *Natural Sciences Education, 46*(1), 1–5.

Vygotsky, L. S. (1978). *Mind in society*. Cambridge, MA: Harvard University Press.

Woods, T. L., Reed, S., Hsi, S., Woods, J. A., & Woods, M. R. (2016). Pilot study using the augmented reality sandbox to teach topographic maps and surficial processes in introductory geology labs. *Journal of Geoscience Education, 64*(3), 199–214.

Yin, R. K. (1994). *Case study research: Design and methods*. London, UK: Sage Publications.

Yoon, S. A., & Wang, J. (2014). Making the invisible visible in science museums through augmented reality devices. *TechTrends, 58*(1), 49–55.

Yoon, S., Elinich, K., Wang, J., Steinmeier, C., & Tucker, S. (2012). Using augmented reality and knowledge-building scaffolds to improve learning in a science museum. *International Journal of Computer-Supported Collaborative Learning, 7*(4), 519–541.

Yoon, S., Anderson, E., Elinich, K., Park, M., & Lin, J. (2018). How augmented reality, text-based, and collaborative scaffolds work synergistically to improve learning in a science museum. *Research in Science and Technology Education, 3*(36), 261–281.

Zhang, J., Hong, H. Y., Scardamalia, M., Teo, C. L., & Morley, E. A. (2011). Sustaining knowledge building as a principle-based innovation at an elementary school. *Journal of the Learning Sciences, 20*(2), 262–307.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.