Spatial Feedback as a Mechanism to Improve topographic Map Literacy Using the Augmented Reality Sandbox

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ABSTRACT

SPATIAL FEEDBACK AS A MECHANISM TO IMPROVE TOPOGRAPHIC MAP LITERACY USING THE AUGMENTED REALITY SANDBOX

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Northern Illinois University, 2018
Nicole D. LaDue, Director

Topographic maps represent three-dimensional (3D) terrain using a system of two-dimensional (2D) symbols. To facilitate students’ understanding of topographic maps, the Augmented Reality (AR) Sandbox reads the elevation of actual sand and projects elevation information onto the sand’s surface (e.g., contour lines). Although over 600 institutions have built AR Sandboxes to help people interpret topographic maps, classroom studies using the AR Sandbox have not found significant gains on topographic map assessments. The present study is a 2×2 design testing the affordances of the AR Sandbox in a one on one, laboratory setting. In the first level of the study, participants interacted with the AR Sandbox (3D feedback) or a computer monitor (2D feedback), which provided spatial feedback on five landforms that participants constructed sequentially in the sandbox. Participants initially built the landforms in the sand with the feedback off (i.e., no projection or monitor displaying topographic map). The feedback was then turned on, and participants compared and contrasted their landform to the target topographic map. Participants were then asked to modify their landform with the feedback on (continuous feedback), or the feedback was turned off (discrete feedback) during modification. A mixed-ANOVA revealed significant gains on a modified version of the Topographic Map Assessment (TMA-B) from pre- to post-intervention \(F(1, 74) = 80.34, p < .001\). A significant interaction revealed that participants in the 2D condition had greater gains \(M = 2.91, SD = 2.48\) than those in the 3D \(M = 1.64, SD = 2.07\) condition \(F(1, 74) = 6.38, p = \)
.014), although both conditions had significant pre- to post-intervention improvement (2D: $t(37) = 7.24, p < .001, d = 1.02$; 3D: $t(39) = 5.01, p < .001, d = 0.64$). On average, the discrete feedback groups spent significantly less intervention time ($M = 48.3, SD = 16.9$) compared to the continuous groups ($M = 58.2, SD = 18.1$) ($F(1, 76) = 6.20, p = .015$). The findings suggest that the AR Sandbox does improve topographic map skill for individual students using this study’s approach and that the most efficient technique engages students in discrete cycles of feedback using a 2D computer monitor.
SPATIAL FEEDBACK AS A MECHANISM TO IMPROVE TOPOGRAPHIC MAP LITERACY USING THE AUGMENTED REALITY SANDBOX

BY

JUSTIN WAYNE MOORE
2018 Justin Wayne Moore

A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY AND ENVIRONMENTAL GEOSCIENCES

Thesis Director:
Nicole D. LaDue
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I am indebted to my advisor, Dr. Nicole LaDue, for her guidance and support during this project. Her drive motivated me through tight deadlines, and her counsel ensured that my efforts stayed on course. Dr. Thomas Shipley offered indispensable assistance with the study’s design and feedback throughout, which extended the impact and relevance of the findings. I also am grateful to Dr. Mark Fischer, who reviewed my work and the laboratory setup and protocol, which improved the data collection procedure. Thank you to Dr. Alecia Santuzzi who recommended a new direction and helped interpret the analysis. I also want to recognize NIU’s Center for the Interdisciplinary Study of Language and Literacy (CISLL), who generously offered the majority of funding for participant stipends through their Proposal or Pilot (PoP) Grant program. Dr. LaDue provided additional support for participant stipends through The Center for Secondary Science and Math Education (CSSME); thank you. I always appreciate the gracious mentorship of Bailey Zo Kreager. I offer a special acknowledgment to Dr. Thomas Pingel; none of this work would possible without his efforts. He built the AR Sandbox with support from NIU’s Research and Artistry Grant, the NIU Physics Department Machine Shop, and a Lab Assistant, Robert Kondratowicz. He also offered much of his personal time to ensure that I had the necessary training to operate the sandbox. Further, Dr. Pingel helped develop the study’s direction and offered constructive feedback and reviews of my writing.
DEDICATION

To my loving and ever-supportive wife, Julia Moore, and my children, Abigail and Oliver.
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CHAPTER 1

Introduction

Geoscience students use topographic maps to explore and learn myriad geographic and geologic concepts. Novice students have difficulty developing the skills necessary to interpret a topographic map’s abstract, two-dimensional (2D) representation of a three-dimensional (3D) space (Clark et al., 2008; Rapp, Culpepper, Kirkby, & Morin, 2007). Topographic map literacy is essential for educational and professional endeavors that require the interpretation of terrain, e.g., geoscience disciplines (Petcovic, Libarkin, & Baker, 2009) and rescue operations (Wilkening & Fabrikant, 2011). Cognitive psychologists are interested in studying spatial thinking to explore mental processes and representations (Ormand et al., 2014; Shipley, Tikoff, Ormand, & Manduca, 2013), and education researchers’ interests are motivated by findings that spatial skills are predictive of success in science, technology, engineering, and mathematics (STEM) fields (Wai, Lubinski, & Benbow, 2009). Studies have shown that training and experience can improve spatial skills (Uttal et al., 2013).

This project investigated the usefulness of augmented reality (AR) to improve topographic map skills using the AR Sandbox. A team of researchers at the UC Davis W.M. Keck Center for Active Visualization in the Earth Sciences (KeckCAVES, 2015) created the AR Sandbox in part to address the difficulty of topographic map interpretation. The tool’s projector overlays elevation information (e.g., contour lines) onto a physical box filled with sand. As one moves the sand to create 3D terrain models, the system senses the elevation adjustments and in
real time, redraws the elevation information. Over 618 institutions world-wide have reported building an AR Sandbox (B. Yikilmaz, personal communication, July 21, 2018). While students have reported increased motivation and engagement, educational studies of the AR Sandbox have not found significant increases in topographic map literacy when implemented with group, free-play, or instructor-led activities (Giorgis, Mahlen, & Anne, 2017; Ryker, McNeal, Atkins, LaDue, & Clark, Christine, 2016; Woods, Reed, Hsi, Woods, & Woods, 2016). I hypothesize that the AR Sandbox’s effectiveness for improving topographic map literacy will improve by restricting the educational intervention to a single individual who is engaged in targeted spatial prediction and feedback.

Background

Virtual and Augmented Reality

Definitions

The genesis of functional virtual reality (VR) is attributed to Ivan Sutherland, who in 1968 created a head-mounted display that visually immersed users in a simple, synthetic environment (Sutherland, 1968). VR is a fully computer generated or artificial environment that completely immerses the user through sensory stimuli, making the real world inaccessible (Merriam-Webster, 2018). Alternatively, augmented reality (AR) allows access to the real world while simultaneously supplementing reality with superimposed virtual information (Azuma, 1997). Scientists at Boeing Computer Services, Research, and Technology devised the phrase “augmented reality” while creating a tool that assisted aircraft manufacturing operations by
overlying virtual information (e.g., templates and formboard diagrams) onto real objects (Caudell & Mizell, 1992). AR devices are characterized by: (1) combination of real and virtual, (2) interactive in real time, and (3) registered in 3D (Azuma, 1997). Researchers have offered assorted definitions of AR (see Bacca, Baldiris, Fabregat, Graf, & Kinshuck, 2014), which essentially distill down to some technical tool or device that superimposes 2D or 3D virtual information onto a real environment to some degree.

Given that AR emerged from VR, a spectrum of characteristics was defined using the virtuality continuum (Figure 1) (Milgram & Kishino, 1994). The left end point represents an environment exclusive to physical items (i.e., real), and the right is an environment existing only of synthetic items (i.e., virtual). Mixed reality occurs along the continuum with varying degrees of real and virtual. AR tends closer to the real environment on the left, and augmented virtuality is towards the right. The tool used for this study, the AR Sandbox, aligns with an AR environment.

![Figure 1](image.png)

Figure 1. Continuum illustrating real to virtual environments (modified from Cheng & Tsai, 2013; Milgram & Kishino, 1994). The AR Sandbox is marked on the continuum within mixed reality or more specifically as augmented reality.

**Types of Augmented Reality**

AR-related researchers have categorized and used AR differently through the years. Types of AR include: marked (or marker-based), markerless, image-based, and location-based.
Marker-based AR requires a device to sense a specific label (e.g., QR or bar code) that references a predetermined action or output (e.g., populating the marked space with an anchored and oriented virtual object). Markerless AR requires a device to sense the environment and relate colors, patterns, geometry, and other cues to reference a predetermined action or output. Location-based AR uses a device’s ability sense position or location via wireless network or GPS, which is used as input or reference. Due to the pace of hardware and software advancement, functional AR classification schemes have evolved. One classification identified two distinct types of AR: (1) marked (or marker-based) and (2) markerless (Pence, 2010). Another study categorized three types: (1) marker-based, (2) markerless, and (3) location-based AR (Wojciechowski & Cellary, 2013). Researchers considered the advancement of natural image processing and combined previous classifications into a general and flexible scheme: (1) image-based and (2) location-based AR (Cheng & Tsai, 2013). Within this scheme, image-based AR includes both marker-based and markerless AR. In an educational AR review of 32 studies, researchers found that image-based AR constituted 71.9% of use in educational settings across all academic levels, while location-based was 21.9% (Bacca et al., 2014). The AR Sandbox’s type of AR may be classified as image-based because the device senses elevation with a 3D camera. The AR Grand Canyon field trip activities studied by Bursztyn, Walker, Shelton, and Pederson (2017) are an example of location-based AR.

The educational framework for this AR-based project was informed by a VR-based learning model (Salzman, Dede, Loftin, & Chen, 1995). The researchers developed the model to further study the relationship between specific affordances of VR and learning facilitation. In a review of AR learning in science, researchers modified the VR-based learning model for AR-based educational studies (Cheng & Tsai, 2013). The AR-based model includes five educational
dimensions that factor into an AR-based educational experience: (1) learning process, (2) learning outcome, (3) interactive experience, (4) learning experience, and (5) learner characteristics (Figure 2). This study focuses on learning process, learning outcome, and learner characteristics. For this project, the model’s learning process dimension was expanded from the kinds of information that a user focuses on to include elements of cognition-based learning models (e.g., prediction, feedback, and mental model transformation). The learning outcome is a measure of comprehension for a given concept (e.g., topographic maps). The learner characteristics describe an individual’s qualities (e.g., domain knowledge or spatial skill) that may influence other dimensions in the model. Given the model above, this study can be characterized as science learning using image-based AR affordances with a focus on the learning process, learning outcomes, and learner characteristics.

Figure 2. An overview of research in AR Sandbox geoscience education (modified from Cheng & Tsai, 2013). The figure situates AR Sandbox studies to date within an educational dimension framework.
The AR Sandbox’s Type of Augmented Reality

The AR Sandbox may be broadly categorized as image-based AR due to the natural image recognition and processing (e.g., sensing the sand’s distance from the camera). Within image-based AR, the AR Sandbox has elements of a projection-based AR. This type requires light to be projected onto a physical medium while simultaneously sensing and reacting to human interactions within the projected field of view (Cebulla, 2013). The projection medium may even be ethereal as with laser plasma technology that creates 3D interactive holograms in mid-air. In the case of the AR Sandbox, elevation information is projected onto the sand’s surface while the 3D camera senses user interactions.

Affordances of the AR Sandbox

The precursor to the AR Sandbox, called Illuminating Clay, was created by the Tangible Media Group at the MIT Media Laboratory (Piper, Ratti, & Ishii, 2002). The current version of the AR Sandbox was created as part of the National Science Foundation-funded Lake Visualization 3D project (Lake Visualization 3D, 2018). The project focuses on freshwater lakes and watershed science in an informal educational environment and aims to drive public understanding and stewardship of freshwater lake ecosystems. To meet those objectives, a team of scientists, science educators, exhibit designers, and evaluation professionals created an AR Sandbox exhibit. Users of the exhibit simply needed to move sand in a box to interact with the device. Once the system recognized that the sand’s height was altered, updated elevation information (e.g., color relief map with contour lines) was projected onto the surface in real time.
Simultaneously, a physically accurate model of flowing water was projected and redrawn many times a second (simulating motion). The water slowly dissipated, and more could be added to the system by holding an object high above the sand. The net result was an interactive 3D model of landforms with real time digital information superimposed on the sand. The AR Sandbox used for this study was built with online resources provided by the Lake Visualization 3D project (Kreylos, 2018a).

**Topographic Maps and Learning Outcomes**

The current project investigates methods to improve topographic map literacy and uses an assessment aligned with those methods to measure learning outcomes. Student’s understanding of topographic maps has been studied by manipulating maps to aid student visualization (Rapp et al., 2007) and evaluating the effectiveness of student strategies for interpreting maps (Clark et al., 2008). More recently, researchers explored the value of gestures and analogy to aid in topographic map literacy (Atit, Weisberg, Newcombe, & Shipley, 2016; Newcombe & Shipley, 2015) and targeted instructional language (Atit et al., 2016). Topographic map comprehension remains a challenge for educators and researchers. The development of AR educational tools, like the AR Sandbox, offers a new opportunity to promote topographic map understanding.

Researchers investigated conditions that may influence topographic map comprehension (Rapp et al., 2007). Students using maps modified via stereo visualization performed better on a topographic map assessment versus maps modified with shaded relief or not modified (i.e., standard topographic maps). Students self-reported a preference for 3D visualization over other map modifications after the study. Rapp et al. (2007) posit that novel topographic map visualizations that embody 2D symbology within a 3D context may aid topographic map
comprehension. Therefore, the AR Sandbox, which is designed to overlay 2D elevation data directly onto a 3D landscape model, should help students understand topographic maps.

Clark et al. (2008) explored the how students conceptualize and interpret topographic maps. While not the primary focus of the study, the researchers found that with the use of traditional instruction student scores improved pre- to post- on topographic map assessment items. Students used a variety of strategies and assumptions to interpret the maps and answer assessment items. Students who used a strategy of elevation comparisons while interpreting topographic maps were less successful. These students were able to successfully interpret symbolic representations (e.g., contour lines), but showed limited success at using elevation to interpret the shape and slope of the terrain. Students who used a strategy of feature recognition were more successful. These students identified a couple features and used pattern matching to successfully visualize the terrain from the topographic map to a surface perspective view. The study reported mixed success when students assumed that the shape of contour lines mirror the shape of a feature or landform. The level of success depended on the type of assessment task (e.g., identification, comparison, or transformation). A persistent misconception was that wavy contour lines were indicative of extreme or high gradient terrain. The current study builds upon the successful strategy of feature recognition, which primarily mirror the shape of the contour lines, to improve students’ topographic map comprehension.

Researchers followed up on a pilot study (Newcombe et al., 2015) and conducted two experiments to study the relationship between TMA performance and instructional interventions to improve topographic map skills (Atit et al., 2016). The first experiment built upon the pilot study and had two treatment groups, Point and Trace and 3D Gestures and Models. The Point and Trace group focused on elevation by tracing contour lines and visualizing the 3D structure.
The 3D Gestures and Models group analyzed topographic maps by using hand gestures to represent 2D landforms that corresponded to 3D models. Analysis showed that results were not an outcome of prior experience measures and both groups significantly outperformed the no instruction control group. Point and Trace was the most effective training, improving overall TMA performance on shape and elevation subscale items. The second experiment examined the impact of instructional language’s influence on TMA performance with 3D gestures held constant. The Elevation language group was instructed that contour lines represent a single elevation and gradient is determined by the distance between adjacent contours. The Shape language group was instructed to focus on the shape of contour lines and to visualize the corresponding 3D structure. Both groups significantly outperformed the control on the overall TMA. Within group results showed that the Shape group numerically performed better on shape items over elevation items, while the Elevation group performed significantly better on elevation items over shape items. Between group differences were also significant, showing that the Elevation group outperformed the Shape group on elevation items, while the Shape group outperformed the Elevation group on shape items. Overall, the studies show that novices benefit from focused gesturing that elucidates complex spatial symbology when coupled with targeted conceptual language. The current study incorporates Atit et al.'s (2016) findings by using an intervention prompt that focuses participants on describing the contour lines’ relationship to elevation and shape.

**Learner Characteristics**

Individuals’ spatial skills lie upon a spectrum of proficiency from novice to expert (Ishikawa & Kastens, 2005). A meta-analysis of 217 studies found that direct training and
experience are effective techniques for improving spatial skills that are durable and transferable (Uttal et al., 2013). Understanding and improving spatial skills is important since they are a strong predictor of success in STEM fields (Wai et al., 2009). Specifically, spatial skills are essential for success in geoscience disciplines (Hegarty, Crookes, Dara-Abrams, & Shipley, 2010; Shipley et al., 2013), and lower and upper level undergraduate geoscience students exhibit a wide range of proficiencies for different spatial skills (Ormand et al., 2014).

Over many decades, numerous spatial skills have been identified and defined, along with accompanying assessments to determine proficiency. In a paper exploring the intersection of cognitive science and spatial thinking within a geoscience context, researchers synthesized spatial skills into five components:

1. Observing, describing, recording, classifying, recognizing, remembering, and communicating the two- or three-dimensional shape, internal structure, orientation and/or position of objects, properties, or processes; (2) mentally manipulating those shapes, structures, orientations, or positions, for example, by rotation, translation, deformation, or partial removal; (3) making interpretations about what caused the objects, properties, or processes to have those particular shapes, structures, orientations, or positions; (4) making predictions about the consequences or implications of the observed shapes, internal structures, orientations, and positions; and (5) using spatial thinking strategies as a shortcut, metaphor, or mental crutch to think about processes or properties that are distributed across some dimension other than distance-space. (Kastens & Ishikawa, 2006, p. 73-74)

Other researchers maintain that a consensus on the components of spatial skills has yet to be reached (Hegarty and Waller, 2005). Thus, a new classification system was created to offer a precise description of spatial skills and the assessments used to measure those skills (Newcombe & Shipley, 2015). The framework consists of a 2×2 classification system with two dimensions: intrinsic-extrinsic and dynamic-static. Intrinsic information defines an object, while extrinsic is the relative relationship between objects. Dynamic information refers an object’s movement or
transformation, while a static object remains fixed. The researchers used the framework to precisely describe 11 spatial skills within a geoscience context, of which 1 extrinsic and 5 intrinsic spatial skills are relevant to the current study’s intervention (Table 1). This study investigated using the AR Sandbox to improve topographic map skill, which has implications for understanding spatial skill development.

**TABLE 1. SPATIAL SKILLS: INTRINSIC AND EXTRINSIC SPATIAL RELATIONS**

**Within-Object (Intrinsic) Spatial Relations (2 static, 4 dynamic)**
1. Disembedding: Isolating and attending to one aspect of a complex display or scene.
2. Categorization: Learning categories based on spatial relations.
3. Visualizing 3D from 2D: Understanding 3D spatial relations presented in a 2D image or drawing.
4. Penetrative thinking: Visualizing spatial relations inside an object.
5. Mental transformations: Visualizing how an object will change over time.

**Between-Object (Extrinsic) Spatial Relations (2 static, 3 dynamic)**
1. Locating self and other objects: Identifying the past or present position of objects in real space and on maps.
2. Alignment: Reasoning about spatial and temporal correspondence (Two important cases are scaling and the use of space as a proxy for time)
3. Perspective taking: Visualizing the appearance of a scene from a different vantage point.
4. Relations among objects, including self, in space: Visualizing the spatial relations defined by multiple locations (e.g., distance between 2 points and angle formed by 3 points; important for making and using maps)
5. Updating movement through space: Visualizing movement of an object relative to other objects (for self this would include route planning)

*Note.* Table directly quoted from Newcombe and Shipley (2015). Modified via italic emphasis.

**Learning Process**

Within the AR learning model, the learning process describes the kinds of information that a user focuses on. Educational psychologists conceptualize learning as a process by which people create and revise a mental representation of a concept (Chi, 2008). From this perspective,
there are pedagogical techniques that can be used to enhance the learning process. One study explored the impact of sketching on 3D geologic diagram comprehension and spatial reasoning (Gagnier, Atit, Ormand, & Shipley, 2017). In another study, researchers investigated the effectiveness of analogies for communicating scales outside of human perception or experience (Resnick, Davatzes, Newcombe, & Shipley, 2017). The intervention developed for the current study was guided by the findings of this prior work.

Chi’s (2008) conceptual change framework proposes that people have mental models of scientific phenomena. A mental model represents an external concept, model, or structure (e.g., atomic structure or water cycle). These internal models may be missing, incomplete, or flawed. While a missing or incomplete missing model may be corrected by adding missing concepts, a flawed mental model is in conflict with the correct model but remains coherent and functional. A flawed model is evident when one is questioned and makes a prediction that is consistently in conflict with a correct model. Chi proposes that one useful technique to move from a flawed to correct mental model may be a holistic approach (Chi, 2008). For example, a student could externalize their mental model via sketching or creating a physical model, and then compare and contrast it with a scientifically correct model. Recent studies have utilized prediction and feedback to investigate whether they are useful learning processes to improve geoscience understanding.

Making predictions to guide investigation is a key component of the scientific process. One study tested whether sketching a prediction using a diagram improved the comprehension of 3D geologic diagrams (Gagnier et al., 2017). There were three conditions in this study: (1) predictive sketching, (2) visualization without sketching, and (3) copying. Using a pre-/post-design, participants had to select the correct 2D slice from within a given 3D spatial diagram.
The researchers found that the most effective intervention method was creating predictive sketches of the inside of 3D models, which outperformed both visualizing the internal structure without sketching and sketching the model but not the inside (i.e., copying). The authors discuss three potential reasons why predictive sketching was effective: (1) Prediction – The task required participants to make inferences about the spatial relationships within the 3D model. (2) Feedback – The sketch was a tangible prediction of the students’ that could be analyzed for accuracy once provided the solution. (3) Externalization – The sketching required students to create a physical representation of their conceptual model, which required thinking about what is inside and how to sketch the predicted model. The findings supported the use of predictive diagrammatic sketching as a method to improve inferences related to spatial associations. Similarly, the AR Sandbox requires participants to externalize their mental model of a topographic map by building a landform. The intervention used in this study involves receiving and analyzing feedback as a learning process to improve topographic map skill.

Comprehending scales outside of direct human perception and experience (e.g., geologic time and nanotechnology) is difficult yet critical to STEM education (Resnick et al., 2017). To investigate ways to improve reasoning at large scales, the authors explored the use of instructional analogies by means of three alignment techniques: structural, progressive, and hierarchical. Each technique afforded participants numerous attempts at analogy creation, and the two experiments they performed used corrective feedback after each analogical step. The first experiment used hierarchical and progressive alignment techniques. The hierarchical alignment intervention generated a persistent (1 month) and improved understanding of the relative time of geologic events with fewer temporal errors when compared to the control treatment. However, when considering the educational implications, the intervention required 1.5 hours, which may
be prohibitive for wide implementation. So, experiment two investigated a more time-efficient intervention using structural analogical alignments via two activities, a clicker feedback activity (i.e., engaging students in a prediction) and a linear visualization activity (i.e., not engaging students in prediction). The clicker feedback activity outperformed the control with higher examination scores and improvement on abstract magnitude number line estimations and this finding was replicated, indicating that it is robust. However, the linear visualization activity underperformed the control with lower examination scores and no improvements on abstract magnitude estimations. Resnick et al. (2017) posits that differences in performance may be a result of successfully aligning multiple external representations. The current AR Sandbox study will leverage the finding that prediction with feedback improves student outcomes and applies this technique to a novel learning scenario.

The intervention designed for the current study engages participants in externalizing a predictive 3D model (i.e., build landform in sandbox), receiving spatial feedback (i.e., projection of topographic map on sand), and contrasting their model to a correct model (e.g., target topographic map prompt). The prediction-feedback cycle is the learning process that is tested in this study using the affordances of the AR Sandbox.

**Current Study**

Topographic map literacy is important for geoscience students and is particularly difficult for novices because it requires interpreting the abstract, 2D symbology representing 3D space. This study investigated the usefulness of spatial feedback as a mechanism to improve topographic map comprehension using the AR Sandbox. The study focused on three primary questions: (1) Does spatial feedback using the AR Sandbox improve topographic map skill, as
measured by the TMA-B? (2) Does 2D or 3D feedback lead to greater gains? (3) Which feedback condition(s) is favorable for practical classroom application?
CHAPTER 2

Methods

This study evaluated the use of the AR Sandbox to significantly improve students’ topographic map interpretation skills, as measured by the Topographic Map Assessment (TMA) (Jacovina, Ormand, Shipley, & Weisberg, 2014). I experimentally tested a 2×2 set of spatial feedback conditions (Figure 3). The first set of conditions compared three-dimensional (3D) feedback from the AR Sandbox’s projector and two-dimensional (2D) feedback from a computer monitor (e.g., Woods et al., 2016) (i.e., the dimensional group). The second set of conditions compared continuous feedback and discrete feedback (i.e., continuity of feedback group). My goal was to determine which approach led to the greatest student improvement on the TMA. The four experimental conditions were (a) 3D continuous (3DC); (b) 3D discrete (3DD); (c) 2D continuous (2DD); (d) 2D discrete (2DD). The study’s dependent variables were the difference in mean scores between the Pre- and Post-TMA-B and the length of time for each intervention. Because the study used a pre- and post-assessment design with an identical instrument, I added a test-retest (TRT) condition to measure the effect of taking the test twice without engaging in the intervention (i.e., the test-retest effect) (Uttal et al., 2013). The study’s independent variables were the 2×2 set of spatial feedback conditions. Additional data were collected concurrently to answer research questions beyond the scope of this thesis study, including: a spatial skill assessment measure, demographic information, 2D image capture of topographic maps and 3D digital elevation models (DEM) of the participants’ landform models constructed in the AR
Sandbox, and qualitative data via video and audio recordings of the intervention. These data were not analyzed as part of this research.

![Figure 3. Experimental spatial feedback conditions (2×2) investigating dimensionality (3D vs. 2D) and continuity of feedback (Continuous vs. Discrete).](image)

### Participants

I recruited 102 student participants from a mid-size U.S. research university in the Midwest with approximately 19,000 total enrolled students and 14,000 undergraduates. Participants completed an electronic Eligibility Survey using Qualtrics that I advertised throughout campus via paper flyers and course announcements (Appendix A). To determine eligibility, survey respondents self-reported experience with topographic maps using a seven-point Likert scale ranging from “1 - no experience” to “7 - a lot of experience” (modified from Atit, Gagnier, & Shipley, 2015). The survey depicted an example topographic map above the item assessing respondents’ experience (Figure 4). My target sample population was those respondents with little to no experience (scales 1-3). Respondents reporting experience levels of 4-5 were considered eligible only after I reviewed a follow-up, open-end question asking for context around their use of topographic maps (e.g., when, where, and how was the map used).
Respondents who selected 6-7 were deemed ineligible to participate and received a notification message upon submission of the survey. While the target population for this study was undergraduates \((n = 99)\), a few graduate students were included \((n = 3)\) because all graduate students self-reported no experience with topographic maps (Table 2). The participants’ average age was 20.4, ranging from 18-28, with 42% male, 56% female, and 2% preferring not to answer. Participants were randomly assigned to 1 of 4 experimental conditions: 3DC, 3DD, 2DC, or 2DD (Table 3). I recruited the TRT group separately using the same instruments to measure the test-retest effect, since I used a pre- and post-assessment study design. Additional information about the TRT group is provided in the Procedure section.

Figure 4. Example topographic map displayed to respondents in the Eligibility Survey (unmodified from Ferdio, 2017).
TABLE 2. PARTICIPANT DEMOGRAPHIC CHARACTERISTICS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, mean ($SD$)</td>
<td>20.4 ± 1.8</td>
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<tr>
<td>Gender</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>43 (42%)</td>
</tr>
<tr>
<td>Female</td>
<td>57 (56%)</td>
</tr>
<tr>
<td>Not Available</td>
<td>2 (3%)</td>
</tr>
<tr>
<td>Education Level</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>Graduate</td>
<td>3 (3%)</td>
</tr>
</tbody>
</table>

TABLE 3. SAMPLE SIZES FOR SPATIAL FEEDBACK CONDITIONS

<table>
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<th></th>
<th>Continuous</th>
<th>Discrete</th>
<th>Total</th>
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<tbody>
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</tr>
<tr>
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<td>20</td>
<td>18</td>
<td>38</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
<td>38</td>
<td>78</td>
</tr>
</tbody>
</table>

$n_{TRT} = 16. N = 94$. Sample sizes exclude outliers (see Results Outliers).

Materials

Augmented Reality Sandbox

In 2015, teams of researchers created the AR Sandbox, in part, to address the difficulty of topographic map interpretation (Figure 5) (KeckCAVES, 2018; LakeViz3D, 2018). The AR Sandbox uses a projector to superimpose elevation information onto a physical box of moveable sand. As one moves the sand, the system senses the elevation adjustments and in real time, redraws the elevation information. The AR Sandbox used in this study had the first-generation Microsoft Kinect 3D camera positioned below the projector, which created immaterial differences from the original setup. The AR Sandbox used in this study used a non-standard setup by generating a black and white topographic map (i.e., no hypsometric color relief) with
equally weighted contour lines and no numerical elevation data (see example output in Figure 6).

This study’s design investigated the impact of 2D and 3D feedback on participants’ learning gains. In the 2D conditions (2DC and 2DD), the computer’s topographic map was displayed on a computer monitor (Dell 1708FPb 17-inch LCD with 1280×1024 resolution) without the use of the projector. In the 3D conditions (3DC and 3DD), the topographic map was projected onto the sand’s surface without using the computer monitor.

Figure 5. Schematic illustration of the AR Sandbox with dimensions (37.5” width not shown) and required components (modified from Kreylos, 2018b).
Figure 6. Screen capture of a topographic map created by the AR Sandbox used in this study.

Topographic Map Assessment Instrument

To assess participants’ topographic map skill, I modified an existing instrument, the TMA (Jacovina et al., 2014). Psychologists, educators, and geoscientists created the TMA and modelled the original items after topographic map assessments found online at the United States Geological Survey’s website. The TMA consisted of 23 items worth 28 maximum points (Table 4). The original validation study found that the instrument demonstrated a high reliability (α = .76) and covered a wide ability range (Newcombe et al., 2015).

I modified the original TMA for this study and henceforth refer to this version as the TMA-Beta (TMA-B) (Appendix B). The present study focused on landform shape rather than
elevation, and therefore I excluded some elevation focused items. In the interest of time required by participants, I also removed redundant TMA items, e.g., “Who walked up a steeper slope?” and “…mark the direction you believe the water would flow.” I added items \((n = 5)\) that related to the landforms included in this study (e.g., Figure 7). The TMA-B consisted of 28 items worth 20.5 possible points and had a mix of closed-end (CE) items \((n_{CE} = 25)\) and open-end (OE) items \((n_{OE} = 3)\). Some items were nested together (e.g., 1a and 1b). The TMA-B had a high reliability \((\alpha = .74)\) for exploratory research (Nunnally & Bernstein, 1967). I assigned TMA-B items subscales based on work done by Newcombe et al. (2015): (1) shape \((n_s = 11)\); (2) elevation \((n_e = 4)\); (3) both \((n_b = 13)\). The original TMA was a “paper and pencil” assessment. I digitized and delivered the TMA-B using Qualtrics to eliminate data entry, increase the efficiency of analysis, and exploit the technological capabilities (e.g., click on diagrams and drag and drop matching of paired topographic map and profile (Figure 8)).

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Scoreable Items</th>
<th>CE Items</th>
<th>OE Items</th>
<th>Possible Points</th>
<th>(\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>23</td>
<td>18</td>
<td>5</td>
<td>28</td>
<td>.76</td>
</tr>
<tr>
<td>TMA-B</td>
<td>28</td>
<td>25</td>
<td>3</td>
<td>20.5</td>
<td>.74</td>
</tr>
</tbody>
</table>

OE – open-end. CE – closed-end
The blue section on the map highlights a type of land form.

What land form is highlighted on the map?

- Hill
- Saddle
- Ridge
- Valley

Figure 7. Example of a landform question added to the original TMA, which was part of the TMA-B used for this study.
I used the TMA-B key (modified from the TMA key) to score CE items and created a rubric to score OE items. A geoscience expert and I used interrater reliability to check OE item scoring validity. Interrater agreement on the 10% of scored items ($n = 48$) was 85%. We examined each discrepancy, discussed disagreements, and reconciled on a single score. In the end, raters were in 100% agreement.

**Participant Background Survey**

The Background Survey collected basic academic, demographic, and experience information (Appendix C). The first item asked participants to self-report experience in clubs and
hobbies known to be associated with spatial skills (e.g., video games, military, and outdoor adventuring). The next two items captured age and sex. The following two items collected participants’ secondary and post-secondary Science, Technology, Engineering, and Math (STEM) courses. I modelled the final items after Atit et al. (2015) and used a seven-point Likert scale for participants to self-assess experience and enjoyment with using maps. The last item asked participants to rate their experience with the AR Sandbox prior to this study.

Spatial Skill Instrument

Since a broad community of researchers (e.g., education researchers and cognitive psychologists) are interested in spatial skills and those skills’ relationships to spatial tasks, I administered a standardized spatial skill assessment, Guay’s (1976) revised Purdue Visualization of Views (VoV) (Eliot & Smith, 1983). The instrument assessed a single spatial skill, perspective taking. Specifically, the VoV measured participant’s skill at imagining the appearance of an unfamiliar object from another view or perspective (e.g., Figure 9). I chose this test because the VoV most closely aligns with this study’s interventional tasks. The participants’ task was to construct and evaluate a 3D model by interpreting a 2D, symbolic representation (i.e., a topographic map). The participants had to connect the 2D, map view perspective of terrain to a physical 3D model. The model then afforded the viewer multiple perspectives from which to correlate the 2D and 3D representations.

I digitized the VoV using Qualtrics (Appendix D). The assessment directions included four pages of instructions with two practice problems and explanations of the solutions. The test consisted of 24 problems and had an 8-minute time limit. I scored the assessment by allocating 1 point per item, for a 24-point maximum score. Correct answers received 1 point, while incorrect
or unanswered items received 0 points. Qualtrics validation rules forced participants to select no more than 1 answer to be able to submit the assessment.

![Diagram of a shape with dashed lines and a small 3D block inside]

Figure 9. Practice problem from the Purdue Visualization of Views. Participants had to select a corner on the top shape’s dashed-line box identifying which viewing position the bottom picture was taken from. For this item, the correct answer is the bottom right corner.

**Design**

This study experimentally tested a 2×2 condition set (Figure 3) to determine which approach yielded improvement on students' topographic map skill, with a pre-/post-assessment design. Using the AR Sandbox, each participant constructed landforms with the sand (e.g., hill) using guiding prompts (e.g., target topographic map and a textual description) and analyzed the similarities and differences between the target topographic map and their constructed landform’s topographic map. Each participant repeated building landforms and analyzing topographic maps using 5 increasingly complex landforms: (a) hill; (b) drumlin; (c) saddle; (d) ridge; (e) stream valley. Each participant experienced a single feedback condition throughout their intervention.
with the AR Sandbox. I randomly assigned participants to a feedback condition: 3DC, 3DD, 2DC, or 2DD.

Procedure

The study was submitted under the title of *Spatial Feedback and the Augmented Reality Sandbox* and approved by NIU’s IRB on December 21, 2017 (Appendix E). There were nine sequential elements for each participant’s data collection session (Figure 10). The study’s protocol and scripts (Appendix F) used the following progression: (1) participants were scheduled using the Eligibility Survey; (2) participants read and signed the consent form; (3) participants took the Pre-TMA-B; (4) participants read the topographic map background; (5) I trained participants how to think aloud while working on a task; (6) we completed the AR Sandbox intervention; (7) participants took the Post-TMA-B; (8) participants completed the Background Survey; (9) participants completed a spatial skill assessment.
Figure 10. Order of elements for the study’s data collection procedure.

The AR Sandbox intervention consisted of multiple steps, and the spatial feedback differed by experimental condition (Figure 11). In the 3D conditions, participants received spatial feedback via the actual topographic map of the sand’s surface projected onto the sand. In the 2D conditions, participants received spatial feedback via the actual topographic map displayed on a standard computer monitor. In the continuous feedback conditions, participants received spatial feedback after the initial landform construction element and for the duration of each iteration. In other words, the sandbox projection or standard computer monitor remained on as the participant modified their landform. In the discrete feedback conditions, participants received spatial feedback only during the analysis and landform identification elements. The
projection or monitor were turned off while participants adjusted their landform. Since pre-/post-
assessment study designs showed an increase in results by only taking and retaking an
assessment, I used a test-retest group of participants who didn’t interact with the AR Sandbox.
The TRT group watched a 30-minute documentary video exploring North American ice ages
(Johnson, Werbe, & Nelson, 2010) and concurrently completed a worksheet (Appendix G) with
11 items focused on the video.

Figure 11. Sequence of AR Sandbox intervention elements overlaid by the continuity of feedback. Each intervention used either the monitor (2D) or projector (3D) exclusively during an AR Sandbox intervention.

Consent to Participate

I scheduled eligible participants for a 90-minute study that began with a consent form.
The consent form described the study’s purpose and conditions during data collection (e.g., video
and audio capture via a head mounted and stationary camera, building, analyzing, and answering
questions about structures in the sandbox, and completing online surveys). Neither camera
captured any identifying facial footage. The form also notified participants that they would receive $20 for full participation. Participation was voluntary and could be withdrawn by the participant at any time. The consent form advised that no foreseeable risks were associated with the study, and all data collected and reported would be kept anonymous, since participants selected an alias (or pseudonym) that I used to label data files. Before a data collection session
commenced, each participant signed and dated in two locations, one for study consent and another for video recording. After signing, I offered each participant an unsigned copy of the consent form for their records.

Pre-TMA-B

After participants completed the consent form, I opened the Qualtrics-based Pre-TMA-B in a Google Chrome browser tab. I informed the participant that they were going to take a survey about maps and reminded them that they were chosen because I was trying to understand how people learn about topographic maps. I then encouraged the participant to try their best and not to worry about making mistakes. I monitored progress and closed the Pre-TMA-B tab when participants were finished.

Topographic Map Background Instruction

After the Pre-TMA-B, participants received instructional information on the basic aspects of topographic maps. I used a modified one-page handout on topographic map concepts based on Atit et al. (2015) (Appendix H). The document defined a topographic map and contour lines. The document then described how contour lines relate to elevation, depicted an increase or decrease in height, and illustrated gradient. The next paragraph described why and who uses topographic maps. The handout concluded by instructing participants to review a figure with two examples of paired topographic maps and their corresponding profile (Figure 12). After the participant read and reviewed the material, I used my pen to highlight key components on the figures by saying: (1) “To highlight, this is a topographic map.” while tracing the outline of the topographic map;
(2) “These are contour lines that show elevation,...” while tracing parts of two contour lines; (3) “…which is shown on the profile, or side view, of the landform.” while tracing a vertical, dashed line downward.

Figure 12. Paired topographic maps and profiles used for background instruction. Modified from Atit et al. (2015).

Think Aloud Training

After the topographic map background instruction, I trained participants on how to think out loud while performing a task. The AR Sandbox intervention required participants to verbally convey the differences and similarities between their landforms’ topographic map and the target topographic map prompt. To frame the think aloud training within the intervention, I created a
handout using People Magazine’s Second Look puzzle feature (Simon, 2018) (Appendix H). The handout consisted of two images where one was digitally altered to have small differences (e.g., removal of a microphone or turning off a light). The think aloud training protocol paralleled the AR Sandbox intervention. Participants first rated the similarity of the two pictures using a scale of 1-10, with 10 representing images that were exactly the same (Figure 13). Next, I defined and described thinking out loud and then asked participants to think aloud while pointing out the differences and similarities between the two images. While the images had 10 discrepancies in total, I proceeded to the next training item after participants identified approximately 3 differences and 3 similarities. Finally, participants described how they would modify the images to make them match each other (e.g., add a microphone or turn on the light). The AR Sandbox intervention followed this training.

Figure 13. Similarity scale to self-report the similarity between two images or maps. Participants used the same scale to report the similarity between a target topographic map prompt and their map.

**AR Sandbox Intervention**

Each participant assigned to an experimental feedback condition (i.e., not the TRT group) completed the AR Sandbox intervention after the think aloud training. Two video cameras were used (e.g., GoPro Hero 5); one camera recorded the participants’ point-of-view (POV) and the other recorded either the sandbox or the computer monitor (perspective), depending on the
condition. Participants began the intervention by putting on the head mounted camera (POV) while I started the AR Sandbox, file management script, and camera management software. After aligning the two video cameras, a POV and a stationary perspective view (i.e., shows height, width, and depth), I provided a brief overview of the AR Sandbox equipment and operation. Participants received the option to wear nitrile gloves, since the silicate-based sand transfers dust to users’ hands.

After preparation, I began recording and explained the task to the participant. The participant had to construct landforms in the AR Sandbox guided by two paper prompts: the target topographic map and textual description of the landform (Figure 14, Appendix I). I positioned the textual description paper directly in front of the participant at eye level. The paper listed all five landform descriptions (e.g., hill, drumlin, saddle, ridge, and stream valley). Each landform description contained two descriptive elements, simple geomorphology and the contour line pattern. I placed the target topographic map paper prompt approximately 35° to the right of each participant at waist level. Although not analyzed for this study, the vertical and horizontal offset between the two paper prompts enabled me to use the POV video data to determine how often and which prompts participants used. Each target topographic map prompt had uniform contour line thickness and no numerical elevation data (i.e., there were no index contours), which mirrored the AR Sandbox’s capabilities and setup. Each landform’s topographic map was on a single sheet of paper that I changed after each construction and analysis iteration. I then explained that while the AR Sandbox’s feedback was turned off (projector or monitor depending on the feedback condition), the participant would build the landform by moving and forming the sand, so afterwards we would both look at the structure and say, “That looks like a hill I might see outside.” The participant notified me when they were finished with construction. I captured a
screen shot of the topographic map and a DEM on the AR Sandbox computer and then turned on the AR Sandbox’s feedback, which displays the topographic map of the participant’s constructed landform. To note, the AR Sandbox output in this study contained noise, which I instructed participants to disregard during analysis. I prompted participants with 3 items, which required them to analyze the similarities and differences between the target topographic map prompt and the AR Sandbox feedback. The first item asked the participant to rate the similarity between what they built and the topographic map prompt using a scale of 1-10 with 10 representing maps that were exactly the same (Figure 13). I placed this scale above the landform textual description prompts for reference. The second item required participants to think aloud while pointing out the differences and similarities between their landform’s topographic map and the target topographic map prompt. My goal was to elicit at least 2-3 responses for the similarities and 2-3 for the differences. If the participant fell short of that goal, I prompted with statements such as, “What about the differences [or similarities]?”, “What else do you notice?”, or “Show me one more difference [or similarity].” The third item required participants to describe how they would adjust their landform (i.e., physically move the sand) to more closely match the landform depicted on the target topographic map prompt. Again, if a participant provided an insufficiently thorough response, I prompted by asking about updates related to the previously identified differences. Then I either turned off the AR Sandbox feedback (discrete conditions) or left the feedback on (continuous conditions). The participant then adjusted the sand to make the landform more closely match the target topographic map prompt. Participants were allowed as much time as each deemed necessary and notified me when their adjustments were complete. I captured the final topographic map and DEM data and worked participants through the same 3 analysis items: self-reported similarity rating, differences and similarities between topographic
maps, and adjustments necessary to make the landforms more closely match. The final item of each iteration asked the participant to identify the landform in the AR Sandbox by pointing to a particular point, gesturing to an area, or tracing a perimeter. Then I turned off the AR Sandbox feedback, leveled the sand, changed the target topographic map prompt, and instructed the participant to build the next landform. I continued this iterative cycle until we worked through all 5 landforms. I removed the POV camera, instructed the participant to clean up their hands if desired, and have a seat to take the Post-TMA-B.

<table>
<thead>
<tr>
<th>Raw Target Map</th>
<th>Target Map Prompt</th>
<th>Textual Description Prompt</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Hill" /></td>
<td><img src="image" alt="Hill" /></td>
<td>A hill is an area of high ground. From a hilltop, the ground slopes down in all directions. On a topographic map, the contour lines are arranged in concentric circles. The inside of the smallest closed circle is the hilltop.</td>
</tr>
</tbody>
</table>

Figure 14. Example of landform prompts used by participants. The raw target map was captured from the target landform that was built in the AR Sandbox. The target map prompt was an unembedded replication. The textual description prompt described the landform’s basic geomorphology and contour line pattern on a topographic map.

**Post-TMA-B**

After the AR Sandbox intervention, participants completed the Post-TMA-B, which was identical to the Pre-TMA-B except I appended the Background Survey. I opened the Qualtrics-based Post-TMA-B in a Google Chrome browser tab. I informed the participant that they were going to take another survey about maps and encouraged the participant to try their best. Participants were prompted to input their alias, so the pre- and post-data could be aligned. I monitored progress and closed the Post-TMA-B tab when participants were finished.
Spatial Skills Assessment (Purdue VoV)

After the Post-TMA-B, I opened the Qualtrics-based VoV in a Google Chrome browser tab. I informed the participant that the next survey covered visualization and to again, try their best. I told participants to work through the first 4 pages and stop. I then responded to questions or comments regarding the task and provided the final instructions (e.g., 8-minute limit and 24 items). When the participant was ready, I instructed them to begin and started an 8-minute, countdown timer. If time expired before completion, I instructed participants to stop working, scroll to the bottom of the survey, and press the submit button to terminate the assessment.

Procedure Conclusion

After we completed all study elements, I notified the participant that the study was over. I handed each participant an envelope with $20 cash and asked them to sign a stipend ledger documenting the session’s time, their alias, and receipt of the stipend. Participants signed using their alias to maintain anonymity. I thanked them for coming in, answered any questions, and showed them out.
CHAPTER 3

Results

Data Preparation

I prepared the Background Survey data by creating 8 data columns from the original 14 items: spatial experience, age, sex, secondary STEM experience, post-secondary STEM experience, map experience, map enjoyment, and AR Sandbox experience. I calculated a spatial experience score by summing the “yes” responses to the first nested item \((n = 6)\). The spatial experience score could range from 0-6. I calculated a secondary STEM experience score by counting how many courses the participant selected from a “select all that apply” item. This score could range from 0-8. I calculated the post-secondary STEM experience score by counting how many courses the participant selected from a “select all that apply” item. This score could range from 0-10. I did not alter the map experience, map enjoyment, and AR Sandbox experience scores. Scores could range from 1-7.

Outliers

Descriptive and inferential statistical analysis of the data were performed using IBM® SPSS® Statistics Version 23. Outliers were identified by retaining the \(z\)-scores for the Pre-TMA-B, Post-TMA-B, and VoV participants. The number of standard deviations \((SD)\) from the mean
is a z-score (Field, 2015). On average, 95.8% of participants’ z-scores fell between -2 and 2, so I regarded those with z-scores less than -2 and greater than 2 as outliers (n = 8). Outliers on the Pre-TMA-B had z-scores in the negative (n = 3) and positive direction (n = 1). The negative z-scores indicated participants at the lowest relative skill level of my sample, and the positive indicated those at the highest relative level. All outliers on the Post-TMA-B (n = 5) had negative z-scores, which indicated that those participants either had likely stopped fully participating over the course of the study (e.g., Keys and Lavender) or were at the lowest relative skill level of my sample (e.g., Fox). I did not remove outliers based on VoV z-scores, since my analysis showed the inclusion to be inconsequential to inferential statistical results. However, a participant who was a VoV outlier was removed based on the Pre-TMA-B (z = 2.14). After I removed outliers from both the Pre- and Post-TMA-B, my final sample size was 94. A priori G*Power 3.1.9.2 analysis (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that 56 was a sufficient sample size to detect a moderate effect of significant differences on an ANOVA.

Descriptive Analysis

Participants’ scores for the Pre-TMA-B, Post-TMA-B, and VoV (n = 94) were normally distributed with skewness and kurtosis values between -1 and 1 (Table 5). Mean scores increased from the Pre-TMA-B (M = 12.61, SD = 3.03) to the Post-TMA-B (M = 14.74, SD = 2.58). The mean for the VoV was 11.33 (SD = 5.56). I separated the data by spatial feedback condition and calculated descriptive statistics for each instrument’s data set (Table 6, Figure 15, Figure 16).
TABLE 5. DESCRIPTIVE STATISTICS OF QUANTITATIVE INSTRUMENTS

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TABLE 6. DESCRIPTIVE STATISTICS BY FEEDBACK CONDITION WITH SEX

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Figure 15. Pre- and Post-TMA-B mean scores grouped by feedback condition. Error bars represent 95% confidence interval.
The TRT group ($n_{TRT} = 16$) performed higher on their Pre-TMA-B than all intervention groups did on their Post-TMA-B. Similarly, the TRT group had the highest mean score on the VoV. These findings indicated that the TRT sample was not representative of the entire study sample. Moreover, the intervention appeared to benefit participants who scored low on the Pre-TMA-B (see Correlation Analysis), and therefore the gains achieved from pre to post by the TRT group were not representative of gains for an equivalent population (see Limitations for possible reasons). Consequently, subsequent analyses exclude the TRT group and have a final sample size of 78.

Figure 16. VoV mean scores grouped by feedback condition. Error bars represent 95% confidence interval.
Since a primary research question was whether 2D or 3D feedback led to greater topographic map learning gains, I evaluated the normality of the sub-samples based on dimension (Table 7). The dimensionally split data for the Pre-TMA-B, Post-TMA-B, and VoV was normally distributed with skewness and kurtosis values between -1 and 1. I examined the histograms and Q-Q (quantile-quantile) plots, which offered more evidence of normality (Appendix J). A Q-Q plot is a scatterplot that charts two sets of quantiles and denotes a normal distribution if the data plots linearly. A non-significant Kolmogorov-Smirnov goodness of fit test further confirmed that the dimensionally split Pre-TMA-B data was normally distributed (Appendix J). The descriptive statistics indicate that the assumptions for parametric statistics were met.

<table>
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<td>Post-TMA-B</td>
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<td>VoV</td>
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</table>

To evaluate research question three on practical classroom application, I analyzed individual landform construction times (in minutes) (Table 8) and total intervention time (i.e., sum of individual landform construction times) (Figure 17). The mean time across all conditions for individual landform construction ranged from 10.2 (valley) to 11.2 (saddle) ($n = 78$). I then
split the individual landform construction times by feedback condition. The results showed that 3DC had the highest time within each landform ($11.6 \leq t_{3DC} \leq 13.1$), except for the hill ($t_{3DC} = 11.6, t_{2DC} = 12.2$). I also found that 2DD consistently had the lowest time within landforms ($8.7 \leq t_{2DD} \leq 9.2$). Likewise, the discrete conditions’ times within landforms were less than the continuous conditions’, with the exception of the ridge ($t_{3DD} = 10.7, t_{2DC} = 9.9$).

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Figure 17. Total intervention time by feedback condition. Total time calculated by summing individual landform construction times. Total Time axis begins at 20 min. Error bars represent 95% confidence interval.

**Correlation Analysis**

I ran bivariate correlations with the Pre- and Post-TMA-B scores, TMA-B difference scores (TMA-B difference = Post-TMA-B score – Pre-TMA-B score), VoV scores, Total Intervention Time, and Background Survey demographic and skills data (Table 9). I used a Pearson correlation to identify associations between variables. The Pearson correlation
coefficient \((-1 \leq r \leq 1)\) is a measure of the strength of the linear relationship between two variables (Field, 2015). A negative \(r\) value represents an inverse linear association between the variables, while a positive \(r\) value represents a direct linear association. As the \(r\) value approaches an end member, the strength of the association increases (Table 10). I found the following relevant associations, which provided an early indicator for worthwhile inferential statistical analyses:

- Moderate negative association between Pre-TMA-B scores and TMA-B difference scores, \((r(77) = -0.579, p < .001)\).
- Weak negative association between TMA-B difference scores and map experience, \((r(77) = -0.298, p = .008)\).
- Non-significant association between total intervention time and all other variables.
- Moderate association between spatial experience and map enjoyment, \((r(77) = 0.417, p < .001)\).
- Weak association between VoV scores and map enjoyment, \((r(77) = 0.256, p = .024)\).
- Non-significant association between TMA-B difference scores and VoV scores.
- Moderate association between Post-TMA-B scores and VoV scores, \((r(77) = 0.516, p < .001)\).
- Moderate association between Pre-TMA-B scores and VoV scores, \((r(77) = 0.423, p < .001)\).
- Weak association between sex and post-secondary STEM experience, \((r(77) = -0.225, p = .048)\).
- Strong association between Pre- and Post-TMA-B scores, \((r(77) = 0.637, p < .001)\).
## 9. PEARSON CORRELATIONS AMONG AR SANDBOX INSTRUMENTS AND MEASURES

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<td>.276*</td>
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<td>.197</td>
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<td>.195</td>
<td>.006</td>
<td>.005</td>
<td>-.027</td>
<td>.233*</td>
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</tbody>
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* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
TABLE 10. PEARSON’S CORRELATION COEFFICIENT CODING

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<tr>
<th>Strength Code</th>
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</tr>
</thead>
<tbody>
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<tr>
<td>Weak</td>
<td>.20 - .39</td>
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<tr>
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<td>.40 - .59</td>
</tr>
<tr>
<td>Strong</td>
<td>.60 - .79</td>
</tr>
<tr>
<td>Very strong</td>
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</tr>
</tbody>
</table>

Source: Evans (1996)

Inferential Analysis

To assess if feedback condition groups effected performance on the TMA-B, I ran a mixed-design analysis of variances (ANOVA) with the Pre- and Post-TMA-B mean scores as the within-subjects factor and the feedback condition groupings as the between-subjects factors. The factors consisted of a dimensional group (2D vs. 3D) and a continuity of feedback group (discrete vs. continuous). There was a significant main effect of TMA-B scores from pre to post, which indicated that overall participant performance improved on the TMA-B, $F(1, 74) = 80.34$, $p < .001$, partial $\eta^2 = .521$. Partial eta squared ($\eta^2$) is an effect size measure used with ANOVAs (Field, 2015). There was also a significant interaction effect between Pre- to Post-TMA-B scores and the dimensional factor, indicating that Pre- to Post-TMA-B change was different between the 2D and 3D groups, $F(1, 74) = 6.38$, $p = .014$, partial $\eta^2 = .079$. A non-significant interaction effect was found between Pre- to Post-TMA-B scores and the continuity factor ($p = .461$). To assess the significant interaction effect between Pre- to Post-TMA-B scores and the 2D and 3D groups, I ran paired-samples $t$-tests for the 2D and 3D groups. On average, 2D group participants’ scores significantly increased from Pre- ($M = 11.32, SD = 2.96$) to Post-TMA-B ($M$
Similarly, on average 3D group participants’ scores significantly increased from Pre- \((M = 12.82, SD = 2.77)\) to Post-TMA-B \((M = 14.46, SD = 2.27)\), \(t(39) = 5.01, p < .001\), and represented a medium-size effect, \(d = 0.64\). While both 2D and 3D groups had a significant difference from Pre- to Post-TMA-B, 2D showed a greater gain \((D_{2D} = 2.91, D_{3D} = 1.64)\) and had a greater effect size \((d_{2D} = 1.02, d_{3D} = 0.64)\).

To gauge how feedback condition effected mean total intervention time (minutes), I used a one-way ANOVA with feedback condition (3DC, 3DD, 2DC, and 2DD) as the between-subjects factor. There was a non-significant effect of feedback condition on the total intervention time, \(F(3, 74) = 2.661, p = .054, \omega^2 = .06\). Omega squared (\(\omega^2\)) is an effect size measure used with ANOVAs (Field, 2015). Since, the effect was close to significance and total intervention times for both discrete feedback conditions (3DD and 2DD) were less than either of the continuous conditions’ time (3DC and 2DC), I grouped the discrete and continuous conditions and analyzed total intervention time. The one-way ANOVA used the continuity of feedback (discrete versus continuous) as the between-subjects factor. There was a significant effect of continuity of feedback on the total intervention time, \(F(1, 76) = 6.202, p = .015, \omega^2 = .06\) (or \(r = .27\)). On average, the discrete feedback group spent significantly less intervention time \((M = 48.3, SD = 16.9)\) compared to the continuous group \((M = 58.2, SD = 18.1)\).

Since there are known gender (i.e., sex) differences on mental rotation tasks (Feng, Spence, & Pratt, 2007; Terlecki, Newcombe, & Little, 2008), and this study’s sample had more females than males \((n_F = 46, n_M = 30, n_{N/A} = 2)\), I ran independent-samples \(t\)-tests to assess differences between sex for Pre-TMA-B scores, Post-TMA-B scores, TMA-B difference scores, and VoV scores (Table 11). While the Pre-TMA-B, Post-TMA-B, and TMA-B difference results
were non-significant, VoV scores showed a significant difference in the mean scores for males ($M = 12.40, SD = 5.58$) and females ($M = 9.65, SD = 4.65$), $t(74) = 2.33, p = .023$, with a marginally medium-size effect, $d = 0.54$.

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th></th>
<th>Female</th>
<th></th>
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<td>$M$</td>
<td>$SD$</td>
<td>$n$</td>
<td>$M$</td>
<td>$SD$</td>
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<tr>
<td>Pre-TMA-B Scores</td>
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<td>2.87</td>
<td>46</td>
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<td>2.93</td>
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<tr>
<td>Post-TMA-B Scores</td>
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<td>14.63</td>
<td>2.82</td>
<td>46</td>
<td>14.07</td>
<td>2.23</td>
</tr>
<tr>
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<td>2.51</td>
<td>46</td>
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<td>VoV Scores</td>
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<td>12.40</td>
<td>5.58</td>
<td>46</td>
<td>9.65</td>
<td>4.65</td>
</tr>
</tbody>
</table>

*Significant at the .05 level (2-tailed).
CHAPTER 4

Discussion and Conclusions

Research Question 1

This study investigated participants’ topographic map skill improvement after using spatial feedback with the AR Sandbox. Overall, participants’ performance significantly improved from Pre- to Post-TMA-B. The study’s design aimed to limit the impact of confounding variables by using a lab intervention, which controlled for potential classroom related distractions and group dynamics. This design also used a participant-led intervention, since Giorgis et al. (2017) found no significant gains using an instructor-led approach. Participants were responsible for externalizing their mental model of landforms encoded via a topographic map and then used the affordances of AR feedback to interpret the error signal and update their mental model (Chi, 2008). The use of prediction, externalization, and feedback has been shown to improve student outcomes (e.g., Crouch, Fagen, Callan, & Mazur, 2004; Gagnier et al., 2017). Results from a comparable TRT group would strengthen the claims made in this study. Nevertheless, employing this approach with the AR Sandbox did lead to significant gains in topographic map skill, a promising finding for the geoscience education community.
Research Question 2

The current study also investigated whether 2D or 3D feedback leads to greater gains in performance from Pre- to Post-TMA-B. The 2D and 3D feedback condition groups showed a significant difference on the degree of improvement from Pre- to Post-TMA-B. Exploring the TMA-B mean differences with \( t \)-tests, the results show that both the 2D and 3D feedback groups had significant improvement. However, the 2D feedback group had greater performance gains and a stronger effect size than 3D, suggesting that it is more promising as a classroom intervention to improve topographic map skill. Although not a focus of the study, no significant difference was found in participant’s degree of improvement from Pre- to Post-TMA-B based on the continuity of feedback groups (discrete and continuous).

The 2D group outperforming the 3D may be attributable to an affordance of the AR Sandbox, the projection of contour lines directly on the 3D model. This feature seems to support topographic map interpretation by reducing the participants’ cognitive load by scaffolding spatial thinking. Specifically, the 3D group’s task did not require participants to visualize 3D from 2D (Newcombe & Shipley, 2015) while analyzing the feedback of the constructed landforms. The 2D group’s task focused on aligning the 3D spatial relations of the landform in the sand to the 2D topographic map feedback from the computer monitor. The TMA-B contains primarily 2D topographic maps, and therefore the 2D condition is better aligned with the outcome variable, as well as real world topographic maps.

The 3D group’s analysis of AR Sandbox feedback may have been confounded due to difficulty with decoupling the 3D model (i.e., the sand) from the feedback (i.e., projected the contour lines). Although I did not fully analyze the think-aloud transcripts, numerous participants
in the 3D group focused on the wrong aspect when asked to describe the similarities and differences between their landform’s topographic map and the target map. For example, Jobe (3DD condition) continued to describe similarities and differences of the landform rather than the contour lines overlain on the model. In particular, Jobe stated, “This [pointing to part of the landform] is built up more than it should be…I think.” After I gently prompted to focus on the topographic map, Jobe followed up with, “Oh…because this map is representing what I built, and it’s talking about what I built compared to [points to target map]…now I get it.” Here Jobe demonstrates how some participants did not recognize that the task was to examine the contour lines on the sand model. Similarly, when some participants were asked how they would modify their landform to more closely match the landform represented by the target topographic map, some would explain how they would alter the contour lines rather than modify the sand model. For example, Vera (3DC condition) stated, “I would just add the contour lines.” After asking Vera to elaborate, he/she traced a contour line while explaining, “Like this. If it was possible.” These two participant cases indicate that some participants were not connecting the relationship between the landform models, the AR Sandbox’s feedback, and the target topographic map, which may have influenced the impact of the intervention.

A third factor influencing the greater gains and effect size for the 2D condition may be spatial relationships related to perspective taking (Newcombe & Shipley, 2015). Topographic map feedback in the 2D group was displayed from a consistent perspective (map view) that aligned directly with the target and TMA-B maps. Since the 3D group’s topographic map feedback was projected onto the 3D model, the map’s perspective changed as the participant moved and was viewed from an oblique angle, both of which are incongruent with the target.
map. Since this study’s population had low prior topographic map experience, the perspective taking component may have reduced the effectiveness of the intervention for the 3D group.

**Research Question 3**

With the widespread implementation of AR Sandboxes, a goal of this research was to converge on a feedback condition that would be favorable for practical classroom application. To evaluate practicality, I considered total intervention time and performance gains on the TMA-B. Total intervention time was not significantly linked to any variable in the correlation analysis. However, the continuity of feedback (discrete vs. continuous) had a significant effect on total intervention time. On average, the discrete feedback group spent significantly less intervention time compared to the continuous group. This finding, coupled with the 2D group outperforming the 3D on the TMA-B, led to a rank ordering of feedback conditions for practical classroom application (Table 12).

<table>
<thead>
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<td>lowest</td>
</tr>
<tr>
<td>2</td>
<td>2DC</td>
<td>moderate</td>
<td>high</td>
</tr>
<tr>
<td>3</td>
<td>3DC</td>
<td>moderate</td>
<td>highest</td>
</tr>
<tr>
<td>4</td>
<td>3DD</td>
<td>lowest</td>
<td>moderate</td>
</tr>
</tbody>
</table>

**Spatial Skills**

While this study investigated using the AR Sandbox to improve topographic map skill, there may be implications for understanding spatial skill development. In this study, the
relationships between the intervention and spatial skills are exploratory and were considered only because spatial skill is of interest to the geoscience education research community. Spatial skill, experience, and interest were measured using the VoV and Background Survey. The VoV assessed participants’ skill with perspective taking, and the Background Survey captured experience with spatially-oriented activities and map enjoyment and experience. The results revealed a non-significant link between TMA-B difference scores and VoV performance. In addition, VoV performance was correlated with both Pre- and Post-TMA-B performance. Thus, spatial skill may have influenced a participant’s Pre- and Post-TMA-B scores, but spatial skill did not determine whether participants benefited from the intervention. In other words, both relatively lower and higher spatial skill participants benefited from the intervention. The results also revealed a link between spatial experience and map enjoyment, which indicates that participants who report higher levels of map enjoyment also participate in spatially-oriented activities. Map enjoyment was also linked to VoV performance. So, participants who report higher levels of map enjoyment also exhibit increased spatial skill. It is important to note that spatial skill tests correlate with other intelligence factors, which were not collected for this study. Therefore, any interpretations about spatial skill and topographic map skill are tenuous and further investigation is required.

Sex

Examining the relationship of participants’ sex to learning outcomes was not a primary component of this study, but notable findings warrant discussion. Males significantly outperformed females on the VoV, which is consistent with extant research about sex differences on spatial tests (Feng et al., 2007; Hegarty, Keenner, Khooshabeh, & Montello, 2009; Terlecki et
al., 2008; Uttal et al., 2013). Sex was also inversely related to post-secondary STEM experience, such that males had more post-secondary STEM experience within the study sample. This may partly explain the significant finding of males outperforming on VoV. Additionally, performance differences between males and females was non-significant for the Pre-TMA-B, Post-TMA-B, and TMA-B gains. So, no interaction between sex and the TMA-B mean scores indicates little reason to investigate the relationship further.

Limitations and Future Work

While the sample sizes for each condition in the 2×2 design were sufficiently powered, the generalizability of the findings may be limited due to a small sample overall. Future work would benefit from recruiting a greater number of participants. Similarly, analysis showed that the TRT group was not similar enough to the other sample population for comparison. The TRT sample had significantly higher Pre-TMA-B scores when compared to the treatment groups’. The TRT group was recruited after the lab intervention groups and at the end of the spring semester during the week of final examination preparation. Future recruitment efforts should interweave treatment and non-treatment sample groups if researchers want to evaluate the test-retest effect. Alternatively, additional data analysis that includes selecting a sub-sample with matching Pre-TMA-B scores among the samples may offer results that strengthen the findings included here.

Correlation statistics indicated the potential of a ceiling effect on TMA-B performance. TMA-B difference scores were inversely related to Pre-TMA-B performance. So, lower Pre-TMA-B scores leave more room for performance gains and conversely, higher Pre-TMA-B scores leave less room for gains from Pre- to Post-TMA-B. Further, TMA-B difference scores
were inversely related to map experience, indicating that as map experience increases, the performance gain on TMA-B decreases. These inverse relationships point to a potential ceiling effect for performance gains related to the intervention. A ceiling effect arises if an assessment’s difficulty is insufficient to adequately measure ability. This can cause score distributions that are compressed near an upward limit of performance and introduce a scoring bias (Uttl, 2005). Even though this study’s participants were not achieving the maximum Post-TMA-B score, they may be outperforming on the TMA-B items that align closely with the intervention (i.e., shape focused items). This aspect requires further investigation into TMA-B subscale items that focus on shape and elevation to see if participants’ scores are compressed near the maximum score.

Total intervention time may have been a confounding variable, since the discrete conditions used less time. A future study might control this variable by setting a time limit for landform construction and adjustment and then comparing the continuity of feedback groups (discrete vs. continuous). Setting a time limit for landform construction and adjustment or reducing the number of landforms constructed during the intervention may make these activities more time efficient without sacrificing on learning outcomes. This would benefit educators with limited class time who want to implement the study’s intervention in a classroom.

The topographic map training used in this study paralleled typical topographic map training for novices. The training focused on the mechanics and rules of contour lines, which were analyzed on a 2D representation of a 3D landscape. To a novice, each contour line may be interpreted as an independent object with little association to adjacent contour lines. However, once someone integrates the meaning of the spatial relationships between contour lines, groups of adjacent contour lines may be more easily recognized and categorized.
as specific landforms. The acquisition of this skill may enable individuals to effectively convert a literal 2D topographic representation into a functional 3D equivalent landscape.

This study captured considerable amounts of data that was not analyzed due to time constraints. These data include: (1) video and audio recordings of interventions from two perspectives simultaneously; (2) self-reported accuracy between participant’s topographic map and the target map; (3) accuracy coding for identification of the landform in the sandbox; (4) screenshots of AR Sandbox-generated topographic maps for every landform (including the target maps); (5) AR Sandbox-generated DEMs of every landform (including the target DEMs). Potential avenues of exploration with this data and future AR Sandbox work include coding of participant’s gestures, language, and point-of-view camera footage. The point-of-view footage could be investigated to identify where participants focused their attention and how often the AR Sandbox feedback was checked against the target map. Additionally, the DEMs may be programmatically analyzed to calculate a metric describing the degree of alignment (or correctness) to the target DEM. Incorporating a DEM alignment tool into the standard AR Sandbox software package provided by KeckCAVES (2018) would enable educators to quickly and accurately measure terrain alignment to a target. Furthermore, the output from such a feature could be transformed into color gradient feedback showing the user areas in the sandbox that are misaligned to a target (i.e., corrective feedback).

Implications for Education

Using the AR Sandbox in a group setting with open play or structured activities and with the standard configuration (i.e., hypsometric color relief, water simulation, and 3D continuous feedback) facilitates student engagement with topographic maps (Giorgis et al., 2017; Reed et
al., 2016; Ryker et al., 2016; Woods et al., 2016). For students with low topographic map skills or those in need of additional instruction, this study demonstrates that targeted prediction and 2D discrete feedback aids topographic map skill acquisition in a one-on-one setting. Participants spent anywhere from 45 to 60 minutes on average during the study’s intervention. Therefore, classroom educators will need to limit or minimize the time a student spends building, analyzing, and modifying landform models. In general, an AR learning experience is more conducive to a classroom setting because it can be a simultaneously shared group event, whereas VR necessitates individual experiences. Research on the value of science-based AR learning and data visualization is important to understand how to help students exploit the affordances. This study focused on topographic map comprehension, or isoelevation, yet many science-related fields and disciplines rely on isoline map literacy. Many examples include: meteorology (isobars and isotherms), oceanography (isobathytherms and isohalines), geology (isopachs), environmental sciences (isoplats and isocons), ecology (isoflors), and social sciences (isocline and isochrone).

Overall, this study’s findings indicate that the AR Sandbox does improve topographic map skill for individual students using prediction and 2D spatial feedback.
REFERENCES


APPENDIX A

PARTICIPANT RECRUITMENT
I made, printed, and posted flyers to recruit undergraduate students from NIU’s campus (Figure 18). The flyer included a link and QR code to the Eligibility Survey (Figure 19). A digital version of the flyer was distributed to NIU faculty in the following disciplines who shared with their introductory classes: Anthropology, Biology, Communications, Foreign Language, Geology, Geography, Health Sciences, Psychology, Secondary Education (Teaching of Science), and Sociology.
PARTICIPATE IN AN
AUGMENTED REALITY STUDY

Who: Current undergraduate students*
What: Spend up to 90 minutes using augmented reality & answering questions. Get $20 cash.
When: March - April
Where: NIU, Davis Hall, Rm 416
How: Take a short survey to qualify:

https://goo.gl/ye3JHt

*Participate in a 90-min research study run by Justin Moore with Dr. LaDue in the Department of Geology and Environmental Geosciences at Northern Illinois University. The study will help researchers understand how students use the Augmented Reality Sandbox to improve topographic map literacy. For more information, contact Justin Moore or Dr. LaDue at 815.753.7935 (jmoore20@niu.edu, nladue@niu.edu).

Figure 18. Recruitment flyer for the AR Sandbox study.
Recruitment Survey

NIU Augmented Reality Study
Recruitment Survey

Directions: This is a brief survey. Please try your best to answer each question.

Rate your experience with maps like the one above:

1 - no experience  2  3  4  5  6  7 - a lot of experience
Please explain the context in which you may have used a topographic map. For example, when, where, and how did you use it?

What is your current educational level at NIU?

- Freshman
- Sophomore
- Junior
- Senior
- Graduate Student
- Other - please specify

Please provide your email address:

Verify email:
APPENDIX B

TOPOGRAPHIC MAP ASSESSMENT BETA (TMA-B)
This study assessed topographic map performance using the TMA-B (Figure 20), a modified version of the TMA (Jakovina et al., 2014). The TMA and TMA-B had similarities and differences in the number of items, maximum points, subscales, and type of item (Table 13).
Q1

Topographic Map Pre-Assessment
Adapted from Jacovina, Ormond, Shipley & Weisberg

Directions: Some of the questions on this assessment may be unfamiliar or challenging. Please try your best to answer each question.

What is your alias for this study?

Imagine you had to walk from point A to point B and wanted to take the flattest path possible.

Click on the path you would choose.

Explain why you chose that particular path in the space below.
Q2

Imagine there is a stream that connects the circle and the square.

Which direction would the water flow?

From the circle to the square

From the square to the circle

Explain why you chose that direction in the space below.

Q3

One person is standing at each point on the map labeled A, B, C, and D. Assume the people are able to use binoculars and there is no vegetation (ex. trees, tall grass, etc.).
Can the people at each of these two points see each other?

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</tr>
<tr>
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</tr>
<tr>
<td>B and C</td>
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<tr>
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<td>✗</td>
</tr>
<tr>
<td>B and D</td>
<td>✗</td>
<td></td>
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</table>

Q4

What is the elevation at point A?
Q5

Imagine Josh traveled on foot from point A to point B, and Amy traveled on foot from point C to point D.

Who walked up a steeper slope?
- Josh from point A to point B
- Amy from point C to point D
- Both paths were the same steepness

How can you tell?

Who traveled a greater vertical distance?
- Josh from point A to point B
- Amy from point C to point D
- Both paths were the same vertical distance

Q6

The lines on this map are contour lines. Answer the question below.
How much does the elevation change moving from one line to another on this map?

40

Q7
Which hill is higher?

Q8

The map shows a cross-section line from point A to point B.

Which elevation profile (below) matches the cross-section of the line AB (above)?

Q9
Imagine you see the view in the picture above. Select the arrow on the map below that indicates where and which direction you think you are facing.
Imagine you see the view in the picture above. Select the arrow on the map below that indicates where and which direction you think you are facing.
Q11

Drag and drop each topographic map (left) to the matching profile (right).

A

B

C

D

E

F

Q12

The blue section on the map highlights a type of land form.
What land form is highlighted on the map?

Hill  Saddle  Ridge  Valley

Q13

The blue section on the map highlights a type of land form.

What land form is highlighted on the map?

Hill  Saddle  Ridge  Valley
Q14

The blue section on the map highlights a type of land form.

What land form is highlighted on the map?

- Hill
- Saddle
- Ridge
- Valley

Q15

The blue section on the map highlights a type of land form.
What land form is highlighted on the map?

- Hill
- Saddle
- Ridge
- Valley

Figure 20. Topographic Map Assessment-Beta (TMA-B) exported via Qualtrics to PDF format.
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D – direction; P – path; SD – speed; ST – spot; R – route; CE – closed-end; OE – open-end

(Continued on following page)
Table 13 (continued)

<table>
<thead>
<tr>
<th>TMA Item</th>
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<th>TMA-B Item</th>
<th>TMA-B Max Points</th>
<th>Subscale Code</th>
<th>Item Type</th>
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</table>

28 20.5

D – direction; P – path; SD – speed; ST – spot; R – route; CE – closed-end; OE – open-end
APPENDIX C

PARTICIPANT BACKGROUND SURVEY
The Background Survey collected basic academic, demographic, and experience information (Figure 21). I prepared the data by creating 8 data columns from the original 14 items: spatial experience, age, sex, secondary STEM experience, post-secondary STEM experience, map experience, map enjoyment, and AR Sandbox experience. I calculated a spatial experience score by summing the “yes” responses to first nested item. The spatial experience score could range from 0-6. I calculated a secondary STEM experience score by counting how many courses the participant selected from a “select all that apply” item. This score could range from 0-8. I calculated the post-secondary STEM experience score by counting how many courses the participant selected from a “select all that apply” item. This score could range from 0-10. I did not alter the map experience, map enjoyment, and AR Sandbox experience scores. Scores could range from 1-7.
Background Questions

What is your alias for this study?


Do you have extensive experience with any of the following activities?

<table>
<thead>
<tr>
<th>Activity</th>
<th>No</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scouts (boy/girl)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Military</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphic design / Art</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Architecture/Planning</td>
<td></td>
<td></td>
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<tr>
<td>Outdoor adventuring</td>
<td></td>
<td></td>
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<tr>
<td>Video games</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

What is your age?


What is your sex?

<table>
<thead>
<tr>
<th>Male</th>
<th>Female</th>
<th>Non-binary</th>
<th>Prefer not to answer</th>
</tr>
</thead>
</table>

Select all the science courses you took in high school.

- Biology
- Chemistry
- Computer Science
- Earth Science
- Environmental Science
- Geography
- Physics
- Physical Science

Select all the science courses you have taken while in college.

- Architecture
- Biology
- Chemistry
- Computer Science
- Engineering
- Environmental Science
- Geography
- Geology
- Graphic Design
- Physics

Were topographic maps taught during any of your courses?

- Yes
- No

Rate your experience with maps in general:

- 1 - no
- 2
- 3
- 4
- 5
- 6
- 7 - a lot of
Figure 21. Background Survey exported via Qualtrics to PDF format.
APPENDIX D

VISUALIZATION OF VIEWS (VOV) SPATIAL ASSESSMENT
I administered a standardized spatial skill assessment, Guay's (1976) revised Purdue Visualization of Views (VoV) (Eliot & Smith, 1983). The instrument assessed a single spatial skill, perspective taking. Specifically, the VoV measured participant’s skill at imagining the appearance of an unfamiliar object from another view or perspective (Figure 22).
Practice1.1

Guay's Visualization of Viewpoints

Directions: This test consists of 24 questions designed to see how well you can tell which viewing position a picture of a three-dimensional object was taken from.

What is your alias for this study?

Shown below is an example of the type of question included in this test.

The example shows an object HOVERING IN THE MIDDLE of the "glass box." Below it there is a picture of the same object from a new viewing position. You are to:
1. look at the picture of the object taken from the new viewing position
2. imagine yourself moving around the "glass box" to find the corner from which this picture was taken
3. click on that corner with your mouse (click again to unselect)

What is the correct answer to the example?
Practice1.2
The correct answer is the upper right corner. Only from there you would have the view that is depicted. Remember that each question has only one correct answer.
Practice2.1
Now look at the next example shown below and try to select the corner of the "glass box" from which the picture was taken. Remember that the object is located in the middle of the "glass box" and you are imagining yourself looking from different corners at the object.
Practice 2.2
The correct answer is the lower right corner.
Note: if you think that the picture was taken from the corner that is covered by the object, click the middle of the cube with your mouse to indicate the corner that is behind the object.

You will have 8 minutes to attempt as many items as possible.

Please wait to begin.

Problems
Figure 22. Purdue Visualization of Views exported via Qualtrics to PDF format.
APPENDIX E

FORMS FOR HUMAN SUBJECTS RESEARCH
Before data collection began, I completed the Collaborative Institutional Training Initiative’s (CITI Program) requisite training in curriculum group Social & Behavioral Research - Basic/Refresher for Stage 1 - Basic Course. I successfully passed the training on September 10, 2017 under the Northern Illinois University institutional affiliation. Successfully completing the CITI Program’s training was a requirement to submit the study to NIU’s Institutional Review Board (IRB). IRB approval is required by U.S. Food and Drug Administration regulations for any research involving human subjects. The study was submitted and approved by NIU’s IRB on December 21, 2017 (Figure 23). NIU’s IRB assigned the study protocol # HS17-0362 under the title of Spatial Feedback and the Augmented Reality Sandbox. The IRB determined that this study met the criteria for a category 7 exemption, which broadly means the research involves no greater than minimal risk to subjects and does not induce stress beyond typical daily life. During the study, I submitted two requests for approval of modifications on February 22, 2018 (Figure 24) and May 9, 2018 (Figure 25). NIU’s IRB determined that both requests did not change the exempt categorization of the project.

The consent form (Figure 26) described the study’s purpose and conditions during data collection. The form also notified participants that they would receive $20 for full participation and that no foreseeable risks were associated with the study. Before I collected data, each participant signed and dated in two locations, one for study consent and another for video recording. Since the TRT group didn’t receive the study’s intervention, I modified the consent form accordingly (Figure 27). After participants’ signed, I offered them an unsigned copy of the consent form for their records.
Exempt Determination

21-Dec-2017
Nicole LaDue
Geology and Environmental Geosciences

RE: Protocol # HS17-0362 "Spatial Feedback and the Augmented Reality Sandbox"

Dear Nicole LaDue,

Your application for institutional review of research involving human subjects was reviewed by Institutional Review Board #1 on 21-Dec-2017 and it was determined that it meets the criteria for exemption 7.

Although this research is exempt, you have responsibilities for the ethical conduct of the research and must comply with the following:

Amendments: You are responsible for reporting any amendments or changes to your research protocol that may affect the determination of exemption and/or the specific category. This may result in your research no longer being eligible for the exemption that has been granted.

Record Keeping: You are responsible for maintaining a copy of all research related records in a secure location, in the event future verification is necessary. At a minimum these documents include: the research protocol, all questionnaires, survey instruments, interview questions and/or data collection instruments associated with this research protocol, recruiting or advertising materials, any consent forms or information sheets given to participants, all correspondence to or from the IRB, and any other pertinent documents.

Please include the protocol number (HS17-0362) on any documents or correspondence sent to the IRB about this study.

If you have questions or need additional information, please contact the Office of Research Compliance and Integrity at 815-753-8588.

Figure 23. Initial NIU IRB exemption determination on December 21, 2017.
Dear Nicole LaDue,

This is to inform you that your request for approval of modifications to the above named project was reviewed on 22-Feb-2018 and it was determined that the modifications you propose do not change the exempt categorization of the project.

Although this research is exempt, you have responsibilities for the ethical conduct of the research and must comply with the following:

**Amendments**: You are responsible for reporting any amendments or changes to your research protocol that may affect the determination of exemption and/or the specific category. This may result in your research no longer being eligible for the exemption that has been granted.

**Record Keeping**: You are responsible for maintaining a copy of all research related records in a secure location, in the event future verification is necessary. At a minimum these documents include: the research protocol, all questionnaires, survey instruments, interview questions and/or data collection instruments associated with this research protocol, recruiting or advertising materials, any consent forms or information sheets given to participants, all correspondence to or from the IRB, and any other pertinent documents.

Please include the protocol number (HS17-0362) on any documents or correspondence sent to the IRB about this study.

If you have questions or need additional information, please contact the Office of Research Compliance and Integrity at 815-753-8588.

Figure 24. First NIU IRB approval of modifications on February 22, 2018.
Figure 25. Second NIU IRB approval of modifications on May 9, 2018.
I agree to participate in the research project titled, “Spatial Feedback and the Augmented Reality Sandbox” being conducted by Justin Moore and Dr. Nicole LaDue at Northern Illinois University. I have been informed that the purpose of the study is to understand how college students use the AR Sandbox to solve geoscience problems.

I understand that if I agree to participate in this study, my point of view will be captured by a head strapped GoPro camera throughout the study. Also, my hand gestures and voice will be video and audio recorded by another GoPro camera. I will be asked to physically construct landforms in the AR Sandbox, make judgments about the degree to which the landform matches the target, explain aloud my steps while solving geoscience problems, and complete a short background questionnaire. This study will take up to 90 minutes to complete.

I am aware that my participation is voluntary and may be withdrawn at any time without penalty or prejudice, and that if I have any additional questions concerning this study, I may contact Dr. Nicole LaDue, nladue@niu.edu, (815) 753-7935. I understand that if I wish to have additional information regarding my rights as a research subject, I may contact The Office of Research Compliance, Integrity & Safety at Northern Illinois University at (815) 753-8588.

I understand that the intended benefits of this study include contributing to scientists’ and educators’ understanding of learning associated with augmented reality science tools. I will receive $20 in exchange for my full participation in this study.

I have been informed that there are no foreseeable risks associated with this study. I understand that all information gathered during this experiment will be kept confidential by storing consent forms in a locked file cabinet. I will choose an alias for my surveys and video and audio recordings so that all of the data collected will be anonymous.

I understand that my consent to participate in this project does not constitute a waiver of any legal rights or redress I might have as a result of my participation, and I acknowledge that I have received a copy of this consent form.

____________________________________  __________________________
Signature of Participant                     Date

I understand that only my voice and hand gestures will be recorded during this study, but my face will not be recorded. Recording files will be assigned a code to protect my identity and will not be associated with my name.

____________________________________  __________________________
Signature of Participant                     Date

Figure 26. Consent form for participation in the intervention group.
I agree to participate in the research project titled, “Spatial Feedback and the Augmented Reality Sandbox” being conducted by Justin Moore and Dr. Nicole LaDue at Northern Illinois University. I have been informed that the purpose of the study is to understand how college students use the AR Sandbox to solve geoscience problems.

I understand that if I agree to participate in this study, I will be asked to complete surveys, a worksheet, and a short background questionnaire. This study may take up to 90 minutes to complete.

I am aware that my participation is voluntary and may be withdrawn at any time without penalty or prejudice, and that if I have any additional questions concerning this study, I may contact Dr. Nicole LaDue, nladue@niu.edu, (815) 753-7935. I understand that if I wish to have additional information regarding my rights as a research subject, I may contact The Office of Research Compliance, Integrity & Safety at Northern Illinois University at (815) 753-8588.

I understand that the intended benefits of this study include contributing to scientists’ and educators’ understanding of learning associated with augmented reality science tools. I will receive $20 in exchange for my full participation in this study.

I have been informed that there are no foreseeable risks associated with this study. I understand that all information gathered during this experiment will be kept confidential by storing consent forms in a locked file cabinet. I will choose an alias for my surveys and worksheet so that all of the data collected will be anonymous.

I understand that my consent to participate in this project does not constitute a waiver of any legal rights or redress I might have as a result of my participation, and I acknowledge that I have received a copy of this consent form.

Signature of Participant ___________________________ Date ___________________________
APPENDIX F

PROTOCOL AND SCRIPTS FOR THE AR SANDBOX INTERVENTION
The current study’s data collection protocol included nine elements (Figure 10). The main protocol and script were the same across spatial feedback conditions but differed slightly during the intervention due to the specific mechanics regarding spatial feedback.

Main Data Collection Protocol and Script

[Work through pre-check to prep lab instruments. Actively wait for participant.]

Greeting & Consent Form:

Hello. My name is …., and I will be running the study today. You can hang you jacket here and place your bag anywhere you like. Are you ready to start?

[If the participant is ready, ask the participant to sit at the desk. The researcher will sit down at a desk near the participant to administer the consent form, TMA, topo background, and think aloud training. Once situated, continue…]

The first paper here is a consent form to participate in this research. When you reach the end of the consent form, sign and date if you agree to participate. Take a moment to read it now and let me know if you have any questions.

[Pause to allow time for them to read the form. When they are finished:]

Would like a copy of the consent form for your records?

[Collect the signed form and place it in the consent form folder. If requested, provide another consent form for the participant’s records.]

You will choose an alias for all the information you provide today. So, none of your responses will be connected to your name or consent form. What alias would you like to use for this study? How do you spell that?

[The researcher will record the alias in lab notebook along with date and time of data collection.]

You’ll use that alias when taking the surveys today.
The next thing you’ll do is take a survey about maps. Please keep in mind that you were selected to participate in this study because we are trying to understand how people learn about topographic maps. Try your best and don’t worry about making mistakes. Let me know if you have questions.

[Give participant the mouse to begin the Pre-TMA-B.]

Let me know when you have finished.

Topographic Map Background Training

Next, you’ll read this background information on topographic maps. Let me know if you have any questions afterwards.

[Hand participant the background 1-pager and allow time to read.]

When finished, the researcher will point to and identify the topo map and contour lines and trace the elevation lines to the profile.

To highlight, this is the topographic map. These are contour lines that show elevation, which is shown on the profile, or side view, of the landform.

Think-aloud Training

So, during the study, I will ask you questions about how you’re using the sandbox. This will help me understand your thought process at certain times.

Let’s try some practice questions now.

[Researcher will hand the participant 1 paper with two photos to compare. Researcher may prompt participant if they are not speaking enough.]

Here are two similar images. One has been digitally altered to have small differences.

On a scale of 1-10, how would you rate the similarity between the top picture and the bottom picture, 10 being exactly the same?

[Note rating in lab notebook.]

Now, I’d like you to think out loud while answering this next question. Thinking aloud means that you will talk out loud while doing a task. You should continue talking and say whatever comes to mind, like what you’re looking at, thinking about, doing, etc.

Questions?
OK. Now think out loud while pointing out the differences and similarities between the top picture and the bottom picture.

[Once they seem to have it, continue. Otherwise prompt the participant to speak more.]

OK. Looks like you have it. You spoke out loud while thinking about the similarities and differences.

Now. How would you change the pictures to more closely match each other?

[When finished, continue.]

Sounds good. Any questions about thinking aloud?

Intervention: AR Sandbox Landform Iterations

Now we’ll move over to the sandbox. You can stand in front of it here.

Before beginning, I need you to put this camera on your head.

This lets me see what you see while you work in the sandbox.

[Hand camera/strap to the participant. Turn on iPad and phone. Connect each device to GoPro.]

How does that feel? Too tight?

[Wait for response and ask to adjust if too tight.]

Too make sure the camera is secure, will you please move your head like this side to side and up and down?

[Ask to adjust if camera isn’t secure.]

Now I’m going to check the camera’s angle. Will you please look at the paper here…the monitor…the map.

[Check angle on phone and adjust camera mount position if needed.]

OK. The camera is set.

I need to sync the two cameras. Please look in the sandbox here.

[Turn flashlight/laser on/off to allow video syncing in post-production.]
Now, we’ll begin working with the sandbox. This sensor reads the height of the sand, sends that information to the laptop, and then creates a real-time topographic map that is shown on the [sand/monitor]. So, your task is to build landforms in the sand…like a hill. When you finish building a hill, we should both be able to look at the structure in the sandbox and say, “That looks like a hill I might see outside.”

Your hands will get a bit dusty while working in the sand. If you like, we have gloves here.

Or wipes over there for after you’re done. Would you like gloves?

[Offer gloves box. Launch AR Sandbox using: SARndbox -fpv -ucl 1.5 -er -10 22 -nm -wo 0]

<TRANSITION TO CONDITION SPECIFIC PROTOCOL AND SCRIPT>

Post-TMA-B

Next, you’ll take another survey about maps. Again, please do your best and let me know if you have questions.

[Prepare 8-minute timer, stipend, & ledger]

VoV Spatial Assessment

The final survey you’ll take is on visualization. Like before, just do your best. The first four pages have instructions with 2 practice questions. Work until you see the message “Please wait to begin” since this will be a timed survey. Let me know if you have questions.

[Give participant the mouse to begin the visualization test.]

Any questions about the task?

You will have 8 minutes to complete the survey. There are 24 questions in total. Ready?

[Start the 8-minute timer.]

Please begin.

[Field questions. Ensure survey is submitted.]

Conclusion and Stipend

That completes the study. Here is $20 for your time.

Is that your alias?

Please sign using your alias. This documents that you received the money.
[Participant is offered $20 cash and signs the stipend ledger.]

That’s it. Thanks for coming in.

3DC Intervention Protocol and Script

OK. You’ll use these two papers to construct landforms in the sandbox.

When we begin, you’ll read the description of the landform and then examine this topographic map. Both describe the same landform.

While the sandbox’s PROJECTOR is off, you’ll build a landform and after you’re done, I’ll turn on the sandbox and ask you a few questions about the similarities and differences between your structure and the topographic map.

Then you’ll adjust your landform to more closely match the topographic map, and I’ll ask questions again.

You’ll make 5 landforms in all. It will get a bit repetitive. Please bear with me.

Any questions before we start?

[Take questions and begin.]

[START LANDFORM CONSTRUCTION]

Please construct the [hill, drumlin, saddle, ridge, stream valley] in the sandbox.

[When done, take screenshot and DEM.]

I will now turn on the sandbox’s PROJECTOR, and it will show a topographic map of the sand’s surface.

Using the topographic map IN THE SAND, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map here?

[Show participant 1-10 question on paper. Nothing like it -> Exactly like it]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.]
What else do you notice?
Please remember to think aloud while you work.
Can you describe out loud what you see?

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map here?

OK. Adjust the sand so your structure more closely matches the landform on the topographic map. You can think aloud if you like.

[When done, take screenshot and DEM.]

Using the topographic map IN THE SAND, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map?

[Show participant 1-10 question on paper.]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.
  What else do you notice?
  Please remember to think aloud while you work.
  Can you describe out loud what you see?]?

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map?

[When done, state the following:]

To answer this next item, you can point to a specific spot, gesture to an area, or trace a perimeter. So, looking in the sandbox, please show me where the [hill, drumlin, saddle, ridge, stream valley] is.

[Turn sandbox off, level sand, & change topo map.]

[END LANDFORM CONSTRUCTION]

We’re done working with the sandbox. You can take that camera off your head.

You can have a seat here.

<TRANSITION TO MAIN PROTOCOL AND SCRIPT>
OK. You’ll use these two papers to construct landforms in the sandbox.

When we begin, you’ll read the description of the landform and then examine this topographic map. Both describe the same landform.

While the sandbox’s PROJECTOR is off, you’ll build a landform and after you’re done, I’ll turn on the sandbox and ask you a few questions about the similarities and differences between your structure and the topographic map.

Then you’ll adjust your landform to more closely match the topographic map, and I’ll ask questions again.

You’ll make 5 landforms in all. It will get a bit repetitive. Please bear with me.

Any questions before we start?

[Take questions and begin.]

[START LANDFORM CONSTRUCTION]

Please construct the [hill, drumlin, saddle, ridge, stream valley] in the sandbox.

[When done, take screenshot and DEM.]

I will now turn on the sandbox’s PROJECTOR, and it will show a topographic map of the sand’s surface.

Using the topographic map IN THE SAND, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map here?

[Show participant 1-10 question on paper. Nothing like it -> Exactly like it]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.
   What else do you notice?
   Please remember to think aloud while you work.
   Can you describe out loud what you see?]

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map here?
I’ll now turn off the sandbox.

OK. Adjust the sand so your structure more closely matches the landform on the topographic map. You can think aloud if you like.

[When done, take screenshot and DEM.]

I will now turn on the sandbox’s PROJECTOR.

Using the topographic map IN THE SAND, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map here?

[Show participant 1-10 question on paper.]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.
  What else do you notice?
  Please remember to think aloud while you work.
  Can you describe out loud what you see?]

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map?

[When done, state the following:]

To answer this next item, you can point to a specific spot, gesture to an area, or trace a perimeter. So, looking in the sandbox, please show me where the [hill, drumlin, saddle, ridge, stream valley] is.

[Turn sandbox off, level sand, & change topo map.]

[END LANDFORM CONSTRUCTION]

We’re done working with the sandbox. You can take that camera off your head.

You can have a seat here.

<TRANSITION TO MAIN PROTOCOL AND SCRIPT>
OK. You’ll use these two papers to construct landforms in the sandbox.

When we begin, you’ll read the description of the landform and then examine this topographic map. Both describe the same landform.

While the sandbox’s MONITOR is off, you’ll build a landform and after you’re done, I’ll turn on the sandbox and ask you a few questions about the similarities and differences between your structure and the topographic map.

Then you’ll adjust your landform to more closely match the topographic map, and I’ll ask questions again.

You’ll make 5 landforms in all. It will get a bit repetitive. Please bear with me.

Any questions before we start?

[Take questions and begin.]

[START LANDFORM CONSTRUCTION]

Please construct the [hill, drumlin, saddle, ridge, stream valley] in the sandbox.

[When done, take screenshot and DEM.]

I will now turn on the sandbox’s MONITOR and it will show a topographic map of the sand’s surface.

Using the topographic map ON THE MONITOR, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map here?

[Show participant 1-10 question on paper. Nothing like it -> Exactly like it]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.
What else do you notice?
Please remember to think aloud while you work.
Can you describe out loud what you see?]

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map here?
OK. Adjust the sand so your structure more closely matches the landform on the topographic map. You can think aloud if you like.

[When done, take screenshot and DEM.]

Using the topographic map ON THE MONITOR, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map?

[Show participant 1-10 question on paper.]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.
   What else do you notice?
   Please remember to think aloud while you work.
   Can you describe out loud what you see?]

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map?

[When done, state the following:]

To answer this next item, you can point to a specific spot, gesture to an area, or trace a perimeter. So, looking in the sandbox, please show me where the [hill, drumlin, saddle, ridge, stream valley] is.

[Turn sandbox off, level sand, & change topo map.]

[END LANDFORM CONSTRUCTION]

We’re done working with the sandbox. You can take that camera off your head.

You can have a seat here.

<TRANSITION TO MAIN PROTOCOL AND SCRIPT>

2DD Intervention Protocol and Script

OK. You’ll use these two papers to construct landforms in the sandbox.
When we begin, you’ll read the description of the landform and then examine this topographic map. Both describe the same landform.

While the sandbox’s MONITOR is off, you’ll build a landform and after you’re done, I’ll turn on the sandbox and ask you a few questions about the similarities and differences between your structure and the topographic map.

Then you’ll adjust your landform to more closely match the topographic map, and I’ll ask questions again.

You’ll make 5 landforms in all. It will get a bit repetitive. Please bear with me.

Any questions before we start?

[Take questions and begin.]

[START LANDFORM CONSTRUCTION]

Please construct the [hill, drumlin, saddle, ridge, stream valley] in the sandbox.

[When done, take screenshot and DEM.]

I will now turn on the sandbox’s MONITOR, and it will show a topographic map of the sand’s surface.

Using the topographic map ON THE MONITOR, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map here?

[Show participant 1-10 question on paper. Nothing like it -> Exactly like it]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.
   What else do you notice?
   Please remember to think aloud while you work.
   Can you describe out loud what you see?]

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map here?

I’ll now turn off the sandbox.

OK. Adjust the sand so your structure more closely matches the landform on the topographic map. You can think aloud if you like.
[When done, take screenshot and DEM.]

I will now turn on the sandbox’s MONITOR.

Using the topographic map ON THE MONITOR, from a scale of 1-10, how would you rate the similarity between what you built and the topographic map here?

[Show participant 1-10 question on paper.]

OK. Now think out loud while you point out the differences and similarities between your landform’s topographic map and this one.

[Prompt participant if not talking enough.
  What else do you notice?
  Please remember to think aloud while you work.
  Can you describe out loud what you see?]

Now, without touching the sand, tell me how you would change your structure to more closely match the landform on the topographic map?

[When done, state the following:]

To answer this next item, you can point to a specific spot, gesture to an area, or trace a perimeter. So, looking in the sandbox, please show me where the [hill, drumlin, saddle, ridge, stream valley] is.

[Turn sandbox off, level sand, & change topo map.]

[END LANDFORM CONSTRUCTION]

We’re done working with the sandbox. You can take that camera off your head.

You can have a seat here.

<TRANSITION TO MAIN PROTOCOL AND SCRIPT>
APPENDIX G

TEST-RETEST GROUP MATERIAL
The TRT group watched a 30-minute documentary video exploring North American ice ages (Johnson, Werbe, & Nelson, 2010) and concurrently completed a worksheet with 11 items focused on the video (Figure 28).
Video: National Geographic: America’s Ice Age (30:15)

Description: Why do we have ice ages and when is the next one due? Chart the progress of different ice ages through the history of our planet, from Snowball Earth hundreds of millions of years ago to the recent ice ages.

Questions:

1. What do the small organisms within the deep-sea mud record?
   Changes in temperature and salinity

2. What caused layers of snow to compact into thick layers of solid ice?
   Increasing weight from additional snow

3. What does Steve Brown from the Illinois State Geological Survey call the unusual rock in the sandy bank that does not appear to belong there?
   An erratic

4. How did these unusual rocks get transported across North America from distances far away?
   Glaciers

5. What is the unusual small hill standing out from the flat Illinois plane?
   Moraine

6. What are the scratches and grooves in rocks carved by glaciers called?
   Striations

7. What is captured in ice cores in between the snow as tiny bubbles?
   Air

8. What are the type of marks found at the top of Bear Mountain called?
   Chatter marks

9. Is the coral stone in the Miami Municipal building made out of?
   Calcium carbonate skeletons of tiny sea creatures

10. What would happen to the size of Florida if sea level dropped?
    Increase

11. What were these changes in sea level directly related to?
    Amount of ice on land

Figure 28. Video worksheet completed by TRT group participants.
APPENDIX H

PARTICIPANT TRAINING MATERIALS FOR THE INTERVENTION
Participants received instructional information on the basic concepts of topographic maps. I used a modified one-page handout on topographic map concepts based on Atit et al. (2015) (Figure 29). I also trained participants on how to think out loud while performing a task. To align the think aloud training within the intervention, I created a handout using People Magazine’s Second Look puzzle feature (Simon, 2018) (Figure 30). The handout consisted of two images where one was digitally altered to have small differences.
Topographic maps provide a way of showing a 3-dimensional landscape on a 2-dimensional surface, like a flat map. **Contour lines** are the main feature of topographic maps. Every point on a single contour line represents the same elevation or height above a reference point (usually sea level). If you were to walk along a contour line, you would not climb up or down, but stay at the same elevation at all times. Moving from one contour line to the next represents a rise or drop in elevation. The distance between lines shows the steepness of a landscape. The closer together the lines, the steeper the terrain.

Topographic maps are most commonly used for navigation so that hikers and travelers can get a sense of the terrain. They are also used by scientists to explore how earth processes and properties vary with topography. Look at the picture below to understand how contour lines on topographic maps relate to the shape of a hill.

Figure 29. Topographic map background training handout.
See if you can find the differences in these two pictures

DOG-EAT-DOG WORLD
Jerry O’Connell got competitive in preparation for the AKC National Championship Dog Show presented by Royal Canin on Dec. 12 in Orlando. The telecast of the event, which airs as part of Animal Planet's New Year's Day programming, is guest-hosted by O’Connell, 43, who has four pups of his own. “It’s the only thing I am on that my children will watch,” he jokingly told People. “It’s a big deal in my household.”

10 CHANGES KEEP SCORE

Figure 30. Think aloud training handout.
APPENDIX I

LANDFORM PROMPTS FOR THE INTERVENTION
The participant had to construct landforms in the AR Sandbox guided by two paper prompts: textual descriptions of the landform and target topographic maps (Figure 31). The textual description paper listed all five landform descriptions. Each landform description contained two descriptive elements, simple geomorphology and the contour line pattern. The topographic maps were created from traced screen shots captures from the AR Sandbox computer after I constructed the target landform in the sandbox.

<table>
<thead>
<tr>
<th>Landform</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill</td>
<td>A hill is an area of high ground. From a hilltop, the ground slopes down in all directions. On a topographic map, the contour lines are arranged in concentric circles. The inside of the smallest closed circle is the hilltop.</td>
</tr>
<tr>
<td>Drumlín</td>
<td>A drumlin is an elongated hill that looks like a half-buried egg. One end of the drumlin will have a steep slope and the other will have a gentle slope. On a topographic map the contour lines are arranged in concentric circles, with lines closer together on the steeper side and further apart on the gentle side.</td>
</tr>
<tr>
<td>Saddle</td>
<td>A saddle is a dip or low point between two hilltops. On a topographic map, the contour lines are arranged in concentric circles for the hills, with an hourglass shape surrounding the hills.</td>
</tr>
<tr>
<td>Ridge</td>
<td>A ridge is an area of high ground that extends in one direction off of a hilltop. On a topographic map, the contour lines are arranged in concentric circles for the hill, with curved lines pointing downhill in the direction the ridge extends.</td>
</tr>
<tr>
<td>Stream Valley</td>
<td>A stream valley is an area of low ground that is cut into a sloping surface. On a topographic map, the contour lines are V-shaped and point uphill, or in the opposite direction that a stream would flow.</td>
</tr>
</tbody>
</table>

Figure 31. Target topographic maps and textual prompts (right) for each landform. The raw topographic maps (left) were screen captured from the AR Sandbox computer of landforms built in the sandbox. The target maps (center) are tracings of the raw maps.
APPENDIX J

NORMALITY ASSUMPTION TESTS FOR TMA-B AND VOV DATA
Data for the Pre-TMA-B, Post-TMA-B, and VoV was analyzed for normal distribution using skewness, kurtosis, histograms, Q-Q plots, and a Kolmogorov-Smirnov (KS) goodness of fit test (Table 5, Figure 32, Figure 33, Figure 34, Figure 35, Figure 36, Figure 37). Histograms of the Pre-TMA-B, Post-TMA-B, and VoV data supported normally distributed results. Q-Q plots of the 2D and 3D split Pre-TMA-B data also supported normality. The KS test confirmed normality of the Pre-TMA-B and VoV data when split into 2D and 3D condition sets.

Figure 32. Histogram of Pre-TMA-B data supporting a normal distribution.
Figure 33. Histogram of Post-TMA-B data supporting a normal distribution.
Figure 34. Histogram of VoV data supporting a normal distribution.
Figure 35. Q-Q plot of 3D Pre-TMA-B data supporting a normal distribution.
Figure 36. Q-Q plot of 2D Pre-TMA-B data supporting a normal distribution.

Figure 37. Kolmogorov-Smirnov test for the Pre-TMA-B and VoV data supporting a normal distribution.