# The Effectiveness of the Augmented Reality Sandbox for Improving Spatial Thinking in Undergraduates

by

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Abstract

Spatial reasoning ability is a necessary skill for success in any of the science, technology, engineering, and mathematics (STEM) domains. Research suggests that spatial thinking ability and exposure to opportunities aimed at developing spatial reasoning skills through educational training could impact a student's decision to select a STEM or non-STEM course of study or impact their decision to remain in STEM career path (Wai et al., 2009, Kell & Lubinski, 2013). Geology is one such field that may be impacted by spatial thinking skills. Students that have less spatial thinking ability could have a more difficult time learning geological concepts (Ishakawa & Kastens, 2005). However, spatial ability is malleable and can improve with intervention and training (Uttal et al., 2013). The heavy reliance on spatial ability to understand many geological concepts, like cartography and topography (Woods et al., 2016; Giorgis et al., 2017), makes researching innovative methods and technologies to train spatial skills a necessity in the geosciences.

Several recent publications have utilized the augmented reality (AR) sandbox in the undergraduate classroom (Woods et al., 2017; Giorgis et al., 2017), and there has been some research suggesting that a student's spatial thinking ability impacts their performance on topographic map assessments after exposure to AR sandbox (McNeal et al., 2019), but there has been no evidence to determine whether the AR sandbox can improve students' spatial reasoning ability. This study aimed to determine the effectiveness of the AR sandbox for improving the spatial thinking of low scoring students. We also explored how students' experiences with the

spatial training activities impacted their self-reflections of their overall spatial thinking skills. Furthermore, we aimed to understand which activities they perceived to best support their spatial skill development to create an effective pedagogical intervention for undergraduate geoscience classrooms.

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## List of Abbreviations

| | |
|---|---|
| AR | augmented reality |
| GIS | geographic information systems |
| SRI | Spatial Reasoning Instrument (Ramful et al., 2017) |
| STEM | Science, Technology, Engineering, and Mathematics |
| MR | mental rotation |
| SOR | spatial orientation |
| SV | spatial visualization |

# Introduction

Spatial reasoning is an essential skill necessary for success in the STEM (science, technology, engineering, and mathematics) domains, especially the geosciences. The ability to understand many geoscience concepts, such as plate tectonics and volcanism, requires certain spatial thinking (Sanchez & Wiley, 2014). For example, making inferences about geologic features in a cross-section requires the ability to use surficial markers to mentally construct those features without being able to physically see the features in the subsurface. Many students may have naturally strong spatial thinking ability, while others may have weaker skills, which could make learning geological concepts more difficult (Ishakawa & Kastens, 2005). A longitudinal study by Kell and Lubinski (2013) suggested that students may self-organize into their majors and careers based on their spatial thinking ability, meaning students may self-select out of STEM domains due to the amount of spatial reasoning ability they possess. For example, if a student has trouble establishing spatial relationships between different landforms on a topographic map, they may not perform as well as a student that can mentally translate two dimensions to three to create profiles and, subsequently, could decide not to remain in the geosciences.

Evidence suggests spatial ability is malleable and can improve with intervention and training (Uttal et al., 2013). A person’s spatial thinking ability and exposure to opportunities aimed at developing their spatial reasoning skills through educational training could impact their decision to select a STEM or non-STEM course of study or impact their decision to remain in STEM (Wai et al., 2009).

The malleability of spatial reasoning skills is of particular interest when developing projects designed to increase student participation in STEM. Additionally, the heavy reliance on spatial ability to perform many geological concepts makes researching innovative methods to train spatial skills a necessity in the geosciences. Over the years, new technology has been developed and assessed for its ability to improve spatial understanding, like using Geographic Information Systems (GIS) to support spatial learning (Lee and Bednarz, 2009; Kim and Bednarz, 2013). Self et al. (1992) claims that specific GIS techniques require a unique understanding of spatial concepts because of the need to interpret and manipulate cartographic features. Since the augmented reality (AR) sandbox also has cartographic and topographic elements (Woods et al., 2016; Giorgis et al., 2017), it may prove useful in training spatial ability.

*AR and the AR Sandbox*

AR is a technology that superimposes virtual components or alterations onto the real world, changing what the user sees as "real" into a manipulated state. The three categories for

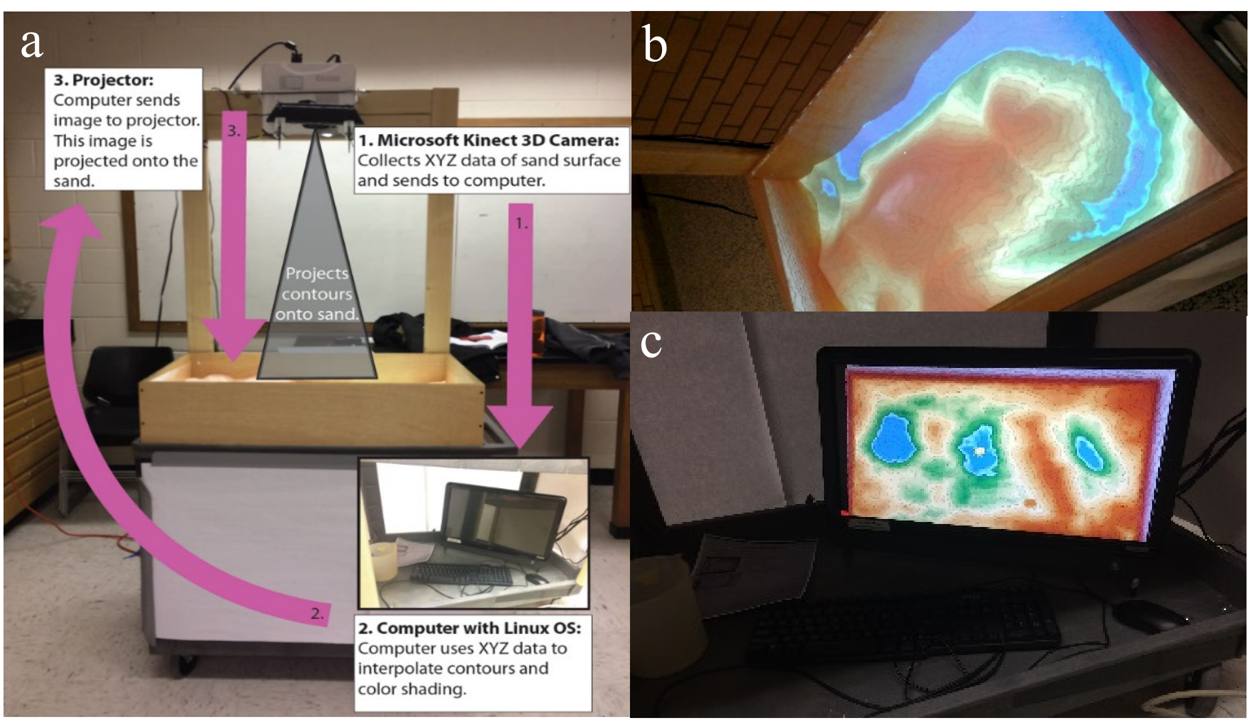


**Figure 1.** a) Schematic of the AR sandbox showing the various components and their communication with one another to produce the contour lines on the surface. b) The colored contour lines on the surface of the sand within the sandbox. c) The contour lines shown on the monitor in the bottom tray of the sandbox cart.

devices that use AR are mobile devices, stationary units, and head-mounted displays (Azuma et al., 2001). The same technology is applied to the AR Sandbox using a depth-sensing camera. The projector and the camera communicate to project contour lines and colors onto the sand's surface (Figure 1). The AR sandbox was first used as a hands-on exhibit as a part of an NSF-funded project designed to explore watersheds in an informal education setting (Reed et al., 2014). Additionally, this technology has been proven to be useful in teaching subjects like topography and slope in introductory geology classes at undergraduate institutions (Ryker et al., 2016; Woods et al., 2016). Improving curriculum by adding more dynamic representations to complement static representations can be beneficial for educators who are addressing students' spatial-skills outcomes (Newcombe, 2016). Today, there are over 650 AR sandboxes in use throughout the United States, ranging from military bases, to museums, to post-secondary academic institutions (Nawaz et al., 2017).

*AR and STEM Education*

AR is a part of a wide range of technologies that are most effectively used for education when students are directly involved in creating their learning experience (Hoban et al., 2013; Prain & Tyler, 2012). When students are creators, they can explore the desired topical concepts by asking those what-if questions generated from hands-on engagement with the technology (Hennessey et al., 2007; Osborne and Hennessey, 2006). Nielsen et al. (2016) created a framework for designing and analyzing AR technology based on reflections from experts in science education. From these reflections, they were able to create criteria in which specific AR technologies would be assessed. These continua were rated based on how important the experts found each continuum, zero being not important and six being most important. The two continua with the highest expert rating were 'interactive' and 'inquiry-based'. Interactive, in this sense, means being able to manipulate and object or environment, and inquiry-based means asking "what-if" questions. The AR sandbox was analyzed using the framework and showed fairly high degrees of interactivity and inquiry-based science, which has been shown in the literature to promote student learning (Hoban et al., 2013; Prain and Tyler, 2012; Hennessey et al., 2007; Osborne & Hennessey, 2006).

*Spatial Skills and Abilities*

Spatial thinking is defined by Uttal et al. (2013) as, "the mental processes of representing, analyzing, and drawing inferences from spatial relations…between objects…or…within objects" (p. 367). The skills that comprise spatial thinking address those between- and within-object relations. Spatial skills are numerous, and their definitions are variable across disciplines and researchers. One well-researched spatial skill in geology is mental brittle transformation, which is the ability to mentally break and reconstruct objects (Resnick and Shipley, 2013). Mental brittle transformation could be trained by reconstructing stratigraphic cross-sections that have been folded and faulted, but the AR sandbox would not be a useful tool for such activities. However, mental rotation, spatial orientation, and spatial visualization are likely to be employed by students while using the AR sandbox, as such they were chosen to be emphasized in this study and are assessed using the Spatial Reasoning Instrument (SRI) (Ramful et al., 2017). Mental rotation involves how a person can turn a two- or three-dimensional object about an axis as a cognitive skill (Shepard and Metzler, 1971) and may be used by surveyors who are using a topographic map to find different landscape features. Spatial orientation requires an understanding of perspective and the relation of an object to a frame of reference (Ramful et al., 2017). Geoscience students in field camp may employ spatial orientation in navigating the field environment and marking the relative positions of outcrop features. Spatial visualization is a term that represents multiple associated tasks. Linn and Petersen (1985) define spatial visualization as "spatial ability tasks that involve complicated, multistep manipulations of spatially presented information" (p. 1484). A structural geologist or geomorphologist may employ this skill in sketching topographic profiles and cross-sections. These three skills may be effectively developed using the AR sandbox if the inherent spatial components can be activated, incorporated into activities using the sandbox, and subsequently used to train students.

## Literature Review

### *Spatial Skills and STEM*

The importance of spatial ability in the STEM domains is solidified through a study by Wai et al. (2009) that compiled 50 years of psychological data to conclude that spatial ability is correlated with STEM achievement and career paths. Forty-thousand random participants were tracked for over 11 years to assess their self-organization into careers based on mathematical, verbal, and spatial ability. The data show that students with high spatial ability excelled in physical science, math/computer science, and engineering in terminal bachelor, master, and doctorate degrees. Students who lack adequate spatial skills tend to self-organize into education, law, and business. Occupations pursued after college strongly resemble those same trends.

### *Training of Spatial Skills in the Geosciences*

Research has shown that constructivism and inquiry-based learning experiences can improve outcomes for science education (Geer & Rudge, 2002; Von Glasersfield, 1995).

Incorporating spatial training strategies and constructivist learning experiences with interactive technologies could dynamically fortify science learning. Spatial training interventions are activities used in psychoeducational research design to improve spatial reasoning ability and have been used in a variety of settings. For example, Titus and Horseman (2009) performed a semester-long study training students from two different populations in spatial visualization. This study assessed the effect of spatial training with certain Spatial Intelligence and Learning Center (SILC)-verified assessment strategies and improved undergraduate student performance, as well as students' overall course grades. In a study conducted by Ormand et al. (2014), students from a variety of geoscience courses experienced gains in spatial skill levels just from being in the course. In a meta-analysis by Uttal et al. (2013), the authors showed that spatial training has the potential to improve performance and participation within STEM domains.

Spatial training with new technologies in the geosciences has been used with GIS to determine whether GIS could influence students' spatial thinking (Lee & Bednarz, 2009; Kim & Bednarz, 2013). In a study by Lee and Bednarz (2009), multiple GIS activities were grouped into spatial visualization, spatial orientation, and spatial relations. A spatial skills test was administered before and after the GIS course and showed gains in spatial reasoning ability, showing that technology having a high spatial component, such as GIS, can train spatial thinking ability.

The AR sandbox's usefulness in engaging students has been documented in a pilot study performed by Woods et al. (2016), which used the AR sandbox to teach topography and surficial process to undergraduate students. While this study did not gather quantitative data on student improvement, it did allow for students to comment on how they felt their learning experience benefited from use with the AR sandbox. The comments were overwhelmingly positive, which suggests that the sandbox does well with engaging students in a classroom setting. This study was confirmed by Soltis et al. (in prep) where students in this study wore skin sensors, which collected skin conductance measurement as a proxy for engagement, during different pedagogical treatments of the AR sandbox. This study found that students were more engaged during AR sandbox activities that had more structure as opposed to "free play" activities.

In a study by Giorgis et al. (2017), the AR sandbox was integrated into the curriculum in an introductory-level geoscience course to determine if the AR sandbox was a better tool for teaching topography than the traditional 2-D, map-based teaching style. The study involved one intervention that lasted 15-20 minutes and one control group given the traditional lesson. The students from both groups were assessed with the same topographic maps test. The study discovered that there was no significant improvement in the experimental group over the control group.

In a study by McNeal et al. (2019), the AR sandbox was implemented in a cross-institutional study where different pedagogical deployments (control, structured, semi-structured, unstructured) were made in the undergraduate classroom. It was found again that there were no differences between treatments (or controls) on student topographic map performance. However, findings showed that student spatial skills (low or high) predicted student performance on the assessments, where high performers did better and that all performers did best in more structured activities, indicating that spatial thinking is an important skill linked to performance but that performance could be mitigated during certain deployments of the AR sandbox. This finding suggests that perhaps there is potential for using the AR sandbox to develop these spatial skills.

While the studies mentioned above do address some critical aspects of student engagement, performance and influences of spatial ability on student performance, these studies do not explicitly test how the AR sandbox can used to develop student spatial thinking skills. Using the AR sandbox could be a very fruitful avenue to develop such skills considering its ability to engage undergraduates. This study aims to explore the AR sandbox's uses in developing spatial thinking ability among undergraduate students.

*Research Questions*

The target population of this research study was undergraduate students enrolled at a four-year institution across many different majors and degree types. The research questions of this study include: (1) What is the distribution of spatial thinking abilities among undergraduate students at a southeastern United States university and do STEM and non-STEM students perform differently?; (2) How does the use of an AR sandbox to teach geology concepts affect the spatial thinking performance of low-scoring students?; and (3) How do students' experiences with the sandbox training activities impact their self-reflections of their overall spatial thinking skills and strategies to solve spatial problems? The first two questions are hypothesis-based and quantitative, while the third is an exploratory qualitative question. Human Subjects Institutional Review Board approved this study under protocol #18-103.

*Hypotheses*

Our hypotheses for the relevant research questions of this study are as follows: (1) There is a relationship between majoring in a STEM field and spatial reasoning ability in that STEM majors will likely have higher spatial thinking skills than their non-STEM counterparts; and (2)

Using the AR sandbox to teach geoscience concepts can facilitate spatial learning in that students exposed to the AR sandbox will have larger pre-post spatial gains as compared to students in a control group.

## Methods & Materials

### *Recruitment and Spatial Thinking Assessment*

The first research question that involved determining the distribution of spatial reasoning ability among students in various majors was addressed by administering a spatial thinking assessment to a large sample of undergraduate students. The Spatial Reasoning Instrument (SRI) (Ramful et al., 2017) was used to measure participants' spatial reasoning ability in the form of an online survey. Large-enrollment classes across departments were targeted, and 567 students completed the survey. The SRI consists of thirty multiple-choice questions comprised of three categories of spatial thinking: mental rotation, spatial orientation, and spatial visualization. Each spatial thinking category is ten questions of the SRI. Factor analysis was used to validate the instrument and the reliability of each construct are as follows: mental rotation is 0.730, spatial orientation is 0.660, spatial visualization is 0.667, and the total internal reliability is 0.849 (Ramful et al., 2017). The survey also collected demographic information, such as major, undergraduate student status or year, ethnicity, gender, ACT/SAT scores, number of geoscience classes taken, experience with toy building blocks, and familiarity with topographic maps. This initial survey acted as the pre-assessment for the low-scoring participants that were asked to complete the AR sandbox intervention.

### *Intervention Study*

Students with scores that fell in the lower 25th percentile (or a score of 19 out of 30) on the initial spatial assessment were invited to participate in the laboratory study with the AR sandbox. Students who elected to participate were randomly assigned to either the experimental or control group ($n_{experimental} = 16$, $n_{control} = 15$).

The participants engaged in a sequence of tasks that lasted approximately one and a half hours in total (Table 1). Both the experimental and control groups completed the same tasks, but the control group took the post-assessment first to capture those students' scores without intervention. The control group still completed the AR sandbox intervention to gain students' narrative data on their experiences with the activity and their perceptions of their spatial reasoning ability, after they completed the post-assessment.

*Table 1. The structure of the laboratory tasks assigned to participants randomly assigned to experimental and control groups*

| Experimental | Control |
|---|---|
| 1. Video<br>2. Intervention<br>3. Interview<br>4. SRI (post-assessment)<br>5. Interview | 1. SRI (post-assessment)<br>2. Interview<br>3. Video<br>4. Intervention<br>5. Interview |

*Note*. Video: 3-minute video that explained mental rotation, spatial orientation, and spatial visualization, and walked participants through an example of how one would employ each of these skills in a non-geoscience context. Intervention: 8-page activity packet combining spatial thinking skills and geoscience concepts. Interview: structured questions designed to ask about general activity experiences, challenges faced, and spatial strategies employed. SRI (post-assessment): the post-assessment to the initial online assessment completed prior.

*AR Sandbox Intervention*

We employed a constructivist framework in the development and implementation of the intervention, in that students were prompted to interact with the sandbox in a way that allowed them to reflect on their experiences. Each page of the activity was designed to train one of the three spatial skills: "Elevation" and "Common Landforms" for mental rotation, "Topographic

Profiles" for spatial visualization, and "Positioning Yourself in the Landscape" for spatial orientation (Appendix A). The learning outcomes were listed on the front page of the activity packet for the participants to understand what they should be able to do and know after engaging in the sandbox with the activity and were validated by geoscience faculty and graduate students (Table 2). The intervention was participant-centered, structured, interactive and required participants to make hypotheses about elements related to topography and map-reading skills. After a hypothesis was made, the participants constructed the model landscape to test their hypothesis and reflected on their responses. An example of an activity page is in Figure 2. Participants were asked to make predictions about which portions of the map had higher and lower elevations before they constructed the landscape in the sandbox. After checking their predictions, the participants were asked to determine what the spatial relationship was between color and elevation.

*Table 2. Learning goals for the AR sandbox activities.*

| What you'll DO | What you'll LEARN |
|---|---|
| 1. Recreate landscapes from topographic maps in the AR sandbox. | 1. How to use colors and numbers to represent elevation. |
| 2. Identify common landforms. | 2. How to identify the characteristics of watersheds. |
| 3. Orient yourself in the landscape to identify features using cardinal and relative directions. | 3. How to interpret steepness of slope. |
| 4. Sketch the landscapes you create in the sandbox in 2-D and 3-D. | 4. How to spatially represent landscapes in 2-D and 3-D. |
| | 5. How to use cardinal and relative directions to give and receive instructions. |

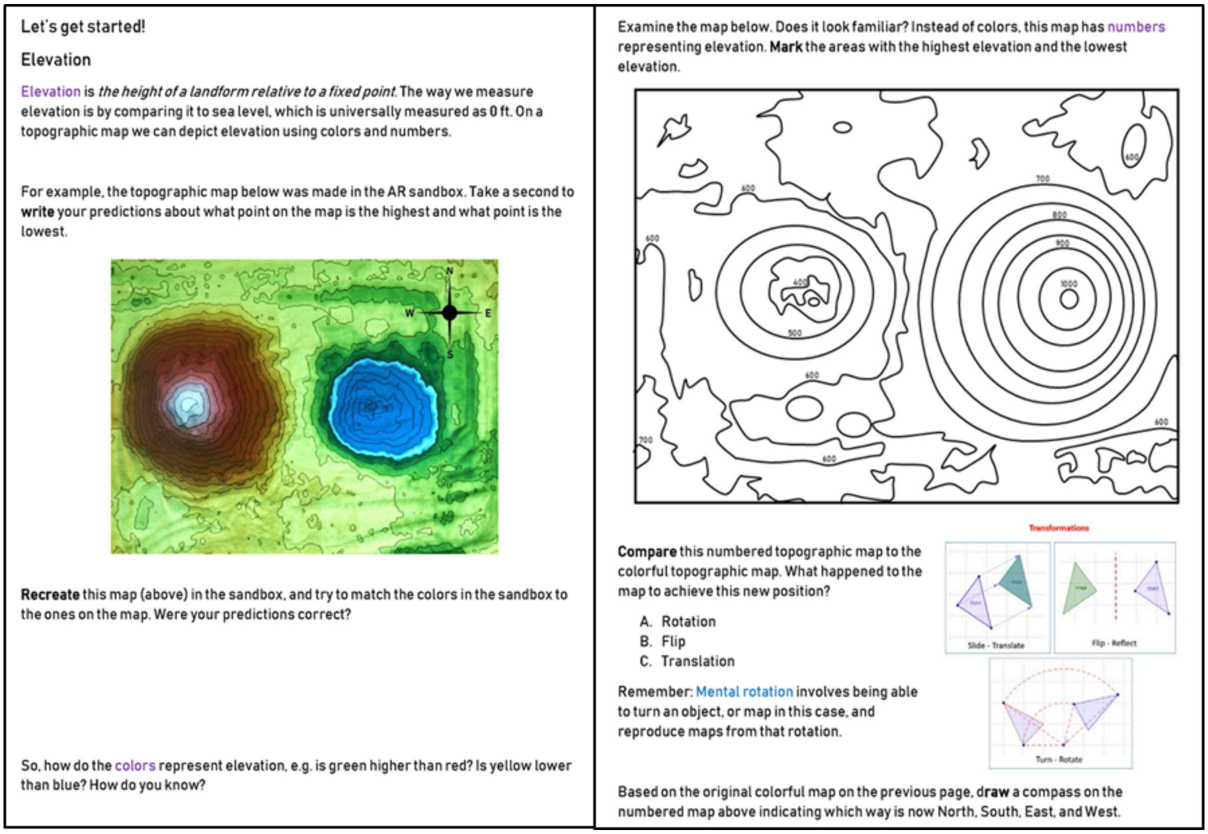


Figure 2. Example of the "Elevation" activity designed to train the mental rotation skill.

*Analysis Procedures*

Statistics including t-tests and the nonparametric Mann-Whitney U test were used to assess the difference in performance between STEM and non-STEM students. A paired t-test was used to determine if there was a significant difference between pre- and post-SRI assessment for those who participated in the intervention study with the sandbox. Thematic analysis was used to analyze the interview data to understand challenges, criticisms, accolades, and strategies participants expressed. A researcher not affiliated with the project coded excerpts from the interview data and deliberated with the researcher until good agreement (.75) was reached using pooled Cohen's kappa. To analyze the narrative data, the transcripts needed to be coded. A code is a word used to ascribe a theme or meaning to an excerpt from narrative data. Code co-occurrences are when two themes overlap. Code co-occurrences were used to yield information about the participants' experiences in the AR sandbox and with the SRI that elucidated the spatial challenges students had, the strategies they used to solve spatial problems, the activities they found most effective in training spatial ability, and the skill they perceived to have improved the most.

*Limitations*

The current research study was limited to just one institution in the U.S. and therefore results cannot be generalized to a larger, more diverse population. Participation in the research was voluntary and as such our sample pool may be biased towards students that were motivated to complete the survey and return to the lab for the follow-up activity. Students also completed the pre-survey online outside of the lab without time constraints, which allowed students to take as much time as they needed and may have also enabled students to not fully engage to their highest potential. Participants completed the AR sandbox intervention only once so we may not been able to fully document the affordances of the AR technology on spatial thinking, especially since all three spatial skills were addressed during this single intervention. After the intervention, participants completed the survey again as a post-test in a quiet laboratory setting with the researcher present, which may have induced higher performance by subjects than that of the online pretest conditions. Also, the pre-post SRI assessment only tested for three spatial skills and although this is an advantage to many other spatial assessments, there are still other spatial skills relevant to the geosciences that could be tested.

## Results

### *Spatial Reasoning Instrument and Differences between STEM and Non-STEM*

Demographic data for participants are reported in Table 3. Descriptive statistics were performed on the SRI data (N=567) to report central tendency and establish the standard for survey participants categorized as "low-performers," which was a score of 19 (range of 0-30), the lower 25% of scores. To ascertain differences between STEM and non-STEM participants, a t-test was ideal. However, since skewness and kurtosis were present when we conducted normality tests (Table 4). The normality tests, Kolmogorov-Smirnov and Shapiro-Wilk, determined that the SRI data were not normally distributed (Table 5). Given these concerns, the independent-samples Mann-Whitney U-test and t-test were used. The results confirmed our hypothesis that STEM majors had higher spatial scores than non-STEM majors. Spatial skills were significantly higher for STEM then non-STEM majors with medium to large effect (MR, $p < .001$; SOR, $p = .004$; SV, $p < .001$, and total SRI, $p < .001$) (Table 6). Please see Appendix B for the majors categorized as STEM and non-STEM.

*Table 3. Demographic data collected from SRI.*

| Demographic | Levels | Count | Percent |
|---|---|---|---|
| Major | Non-STEM | 261 | 46 |
| | STEM | 294 | 52 |
| | Undeclared | 10 | 2 |
| Gender | Female | 352 | 63 |
| | Male | 211 | 37 |
| Academic Status | Freshman | 190 | 36 |
| | Sophomore | 182 | 34 |
| | Junior | 93 | 17 |
| | Senior | 50 | 9 |
| | Super-senior | 20 | 4 |
| Topographic Map Familiarity | Very unfamiliar | 64 | 23 |
| | Somewhat unfamiliar | 112 | 41 |
| | Somewhat familiar | 28 | 10 |
| | Very familiar | 71 | 26 |
| Race | Non-White | 95 | 17 |

| | | | |
|---|---|---|---|
| | White | 472 | 83 |

*Table 4. Descriptive statistics for survey.*

| | | MR | SOR | SV | TOTAL |
|---|---|---|---|---|---|
| N | | 567 | 567 | 567 | 567 |
| Mean | | 7.43 | 8.82 | 6.23 | 22.48 |
| Std. Error of Mean | | .097 | .068 | .104 | .229 |
| Std. Deviation | | 2.301 | 1.611 | 2.481 | 5.452 |
| Skewness | | -.750 | -2.033 | -.202 | -.680 |
| Kurtosis | | -.232 | 4.591 | -1.023 | -.273 |
| Minimum | | 0 | 2 | 0 | 5 |
| Maximum | | 10 | 10 | 10 | 30 |
| Percentiles | 25 | 6.00 | 8.00 | 4.00 | 19.00 |
| | 50 | 8.00 | 9.00 | 6.00 | 23.00 |
| | 75 | 9.00 | 10.00 | 8.00 | 27.00 |

*Table 5. Normality test for SRI scores.*

| | Kolmogorov-Smirnov[a] | | | Shapiro-Wilk | | |
|---|---|---|---|---|---|---|
| | Statistic | df | Sig. | Statistic | df | Sig. |
| TOTAL | .119 | 567 | .000 | .941 | 567 | .000 |

a. Lilliefors Significance Correction

*Table 6. Statistical tests showing differences in group means between STEM and non-STEM.*

| | t-test for Equality of Means | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 95% Confidence Interval of the Difference | | | |
| | t | df | *p* | *d*[a] | Mean Diff. | Std. Error Diff. | Lower | Upper | Mann-Whitney U Test | *d*[a] |
| MR | 6.83 | 480.86 | <.000 | .619 | 1.30 | .19 | .93 | 1.67 | ** | .537 |
| SOR | 4.04 | 429.43 | <.000 | .347 | .56 | .14 | .29 | .83 | ** | .235 |
| SV | 5.92 | 513.26 | <.000 | .508 | 1.23 | .21 | .82 | 1.63 | ** | .488 |
| TOTAL | 6.82 | 473.97 | <.000 | .586 | 3.09 | .45 | 2.20 | 3.97 | ** | .528 |

**Significant at the .01 level.
a. Cohen's *d*.
Note. MR=mental rotation, SOR=spatial visualization, SV=spatial visualization.

*Pre- and Post-SRI Performance*

Table 7 provides the descriptive statistics for each measurement to qualitatively compare differences in performance between conditions, while Table 8 shows the demographics of the sample that participated in the lab study. A paired samples t-test was determined sufficient to test if there were differences in pre- and post-SRI scores as this sample was normally distributed determined by the K-S and S-W tests. We found there was a significant difference from pre- to post-test and large effect sizes in mental rotation (*p*=.012, d=.787), spatial orientation (*p*=.001, d=1.309), and total SRI score (*p*<.001, d=1.306) for the experimental group. We also found significant improvement and large effect sizes in mental rotation (p=.001, d=1.130), spatial orientation (p=.026, d=.752), and total SRI score (p<.001, 1.413) for the control group, which are the same improved skills as the experimental group. Spatial visualization improvements were not significant for either the experimental (p=.321, d=.332) or the control (p=.082, d=.644) (Table 9).

*Table 7. Descriptive statistics of pre- and post-assessment for experimental and control groups.*

| Experimental | N | Mean | Std. Deviation | Control | N | Mean | Std. Deviation |
|---|---|---|---|---|---|---|---|
| Pre-MR | 16 | 4.44 | 1.711 | Pre-MR | 15 | 4.67 | 2.024 |
| Pre-SOR | 16 | 6.37 | 2.391 | Pre-SOR | 15 | 7.47 | 1.552 |
| Pre-SV | 16 | 3.44 | 1.315 | Pre-SV | 15 | 3.87 | 1.060 |
| Pre-TOTAL | 16 | 14.25 | 2.955 | Pre-TOTAL | 15 | 16.00 | 2.854 |
| Post-MR | 16 | 5.94 | 2.081 | Post-MR | 15 | 6.80 | 1.740 |
| Post-SOR | 16 | 8.75 | .931 | Post-SOR | 15 | 8.47 | 1.060 |
| Post-SV | 16 | 4.00 | 2.000 | Post-SV | 15 | 4.87 | 1.922 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Post-TOTAL | 16 | 18.69 | 3.790 | Post-TOTAL | 15 | 20.13 | 2.997 |

*Table 8. Demographic data for laboratory participants.*

| Demographic | Levels | Count | Percent |
|---|---|---|---|
| Major | Non-STEM | 16 | 52 |
| | STEM | 15 | 48 |
| Gender | Female | 20 | 65 |
| | Male | 11 | 35 |
| Academic Status | Freshman | 11 | 35 |
| | Sophomore | 10 | 32 |
| | Junior | 4 | 13 |
| | Senior | 4 | 13 |
| | Super-senior | 2 | 6 |
| Topographic Map Familiarity | Very unfamiliar | 6 | 2 |
| | Somewhat unfamiliar | 10 | 4 |
| | Somewhat familiar | 12 | 4 |
| | Very familiar | 3 | 1 |
| Race | Non-White | 8 | 26 |
| | White | 23 | 74 |

*Table 9. Paired samples t-test showing pre- to post-assessment differences and effect sizes of experimental and control groups.*

| | Paired Differences | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean Diff. (*SD*) | Std. Error Mean | 95% Confidence Interval of the Difference Lower | Upper | T | df | *p* | Cohen's *d** |
| Experimental | | | | | | | | |
| MR | -1.50 (*2.10*) | .52 | -2.62 | -.38 | -2.86 | 15 | .012 | .787 |
| SOR | -2.37 (*2.19*) | .55 | -3.54 | -1.21 | -4.34 | 15 | .001 | 1.309 |
| SV | -.56 (*2.19*) | .55 | -1.73 | .60 | -1.03 | 15 | .321 | .332 |
| TOTAL | -4.438 (*3.92*) | .98 | -6.52 | -2.35 | -4.53 | 15 | <.000 | 1.306 |
| Control | | | | | | | | |
| MR | -2.13 (*1.96*) | .51 | -3.22 | -1.05 | -4.22 | 14 | .001 | 1.130 |
| SOR | -1.00 (*1.56*) | .40 | -1.86 | -.14 | -2.48 | 14 | .026 | .752 |
| SV | -1.00 (*2.07*) | .53 | -2.15 | -.15 | -1.87 | 14 | .082 | .644 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| TOTAL | -4.13 (*3.50*) | .90 | -6.07 | -2.19 | -4.57 | 14 | <.000 | 1.413 |

*Calculated using pooled variance.

*Student Experiences from the AR Sandbox Activity and SRI*

A summary of challenges and strategies participants acknowledged are listed in Table 10, where the percent of code co-occurrences between either challenge or strategy and each spatial skill is listed. The majority of challenges are shared between mental rotation and spatial visualization, while spatial orientation has the fewest number of challenges. “Complex rotation” accounts for 25% of challenges participants reported. “Perspective-taking was a unique challenge for participants, but it was also a unique strategy, one that is not reported by participants in either mental rotation or spatial visualization. A strategy unique to spatial visualization was “working backwards.” Participants had the greatest number of codes for spatial visualization challenges (n=55) and the least amount of codes for strategies (n=9). On the opposite end, spatial orientation had the fewest codes for challenges (n=6) and the greatest amount of codes of strategies (n=54). Sitting in the middle, between spatial orientation and visualization, mental rotation had 41 codes for challenges and 24 for strategies.

*Table 10. Spatial challenges and strategies students identified for each spatial skill.*

| Challenges | % MR | % SOR | % SV | % Total |
|---|---|---|---|---|
| 3D Shapes | 5 | | 4 | 4 |
| Complex rotation | 54 | 17 | 4 | 25 |
| Directions | 7 | | 2 | 4 |
| Point(s) of reference | 2 | 17 | | 2 |
| Folding | | | 31 | 17 |
| General inexperience | | | 4 | 2 |
| Mental manipulation | 7 | | 20 | 14 |
| Overall complexity | 2 | | 15 | 9 |
| Paper cut-outs | 2 | | 15 | 9 |

| | | | | |
|---|---|---|---|---|
| Perspective-taking | | 33 | | 2 |
| Recognizing differences | 20 | 33 | | 10 |
| Reflections | | | 7 | 4 |
| Total Number of Codes | 41 | 6 | 55 | 102 |

| Strategies | % MR | % SOR | % SV | % Total |
|---|---|---|---|---|
| Talk/Think through | 8 | 1 | 22 | 6 |
| Spatial relationships | 13 | 3 | | 9 |
| Flipping | 4 | 1 | | 2 |
| Mental manipulation | 4 | 1 | | 2 |
| Perspective-taking | | 23 | | 47 |
| Rotating/Gesturing | 13 | 1 | | 4 |
| Process of elimination | 21 | | 11 | 7 |
| Rotating by degrees | 13 | | | 3 |
| Selecting reference point | 25 | 2 | 56 | 16 |
| Working backwards | | | 11 | 1 |
| Total Number of Codes | 24 | 54 | 9 | 87 |

When participants were asked to assess certain spatial test items to determine their perception of degree of difficulty, spatial visualization had the greatest percentage of “hard” codes (69%) and the greatest percentage of codes for spatial challenges (54%) (Table 11). Spatial orientation had the fewest percentage of “hard” codes (11%) and the fewest percentage of for spatial challenges (6%) (Table 11). Inversely, spatial orientation had the greatest percentage of code co-occurrences for “easy” (89%) and the greatest percentage of codes for spatial strategies (62%). Spatial visualization had the fewest percentage of “easy” codes (31%) and the fewest percentage of codes for strategies (10%) (Table 12).

*Table 11. Spatial challenges and participant examples.*

| | % of Spatial Challenges | % of Difficulty Perceptions(“hard” codes/total) | Example Spatial Challenge | Example Excerpt |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| MR | 40% | 45% (40/89) | Recognizing differences. | "10, I totally guessed on this one. I'd no idea because like, 'Which of the following represents a rotation of the model above?' They all look exactly the same to me, and they all could be rotations. I was confused." |
| SOR | 6% | 11% (13/122) | Establishing point(s) of reference. | "14 was difficult because I wish there was a door point of reference or something. All I had was this Mr. Sam. I don't know. This one was just hard. I couldn't figure out who was John or Jill." |
| SV | 54% | 69% (73/105) | Mentally manipulating objects. | "Six, difficult. Again, with the folding, it was hard for me to visualize without having something to actually fold or draw out. Doing it in my head is difficult, but if I drew it out, that would be easier." |

*Note*. % of Spatial Challenges=the number of occurrences that were coded both with the specific spatial skill (MR, SOR, or SV) and a specific challenge. % of Difficulty Perceptions=the number of occurrences that were coded for each skill as being "hard" by total codes for SRI ability perceptions.

*Table 12. Spatial strategies and participant examples.*

| | % of Spatial Strategies | % of Difficulty Perceptions("easy" codes/total) | Example Spatial Challenge | Example Excerpt |
|---|---|---|---|---|
| MR | 28% | 55% (49/89) | Selecting a focal point. | "The thing I looked at was to make sure that the big side was on the right, the smaller side was on the left. I just looked at all of them and decided." |
| SOR | 62% | 89% (109/122) | Perspective-taking. | "The ones where you could think about from one position, like the second question which was on Kate, |

| | | | | |
|---|---|---|---|---|
| | | | | "Where is the vase in place of Kate's view?" It's easier to put it in her perspective like, "It's going to be to her right," because that's the way you're facing." |
| SV | 10% | 31% (32/105) | Process of elimination. | "18 was pretty hard, because for each option I folded up the shape in my head and had to determine which one wasn't. It took a while to go through in my head." |

*Note*. % of Spatial Challenges=the number of occurrences that were coded both with the specific spatial skill (MR, SOR, or SV) and a specific challenge. % of Difficulty Perceptions=the number of occurrences that were coded for each skill as being "easy" by total codes for SRI ability perceptions.

When participants were asked how they would apply each spatial skill, spatial orientation had the most reported applications shown in Table 13, with the largest application in social settings like determining who to sit next to at dinner. Organizational applications like arranging furniture in a room was reported most for mental rotation. The most reported application for spatial visualization was construction, like assembling furniture or putting a box together. Spatial visualization also had the most reports of no application.

*Table 13. Student-reported applications of each spatial skill.*

| Applications | % MR | % SOR | % SV | % Total |
|---|---|---|---|---|
| Academic | 8 | 2 | 6 | 14 |
| Related to Anatomy | 1 | | 1 | 2 |
| Constructional | 1 | | 18 | 17 |
| Navigational | 7 | 9 | | 14 |
| Organizational | 11 | 7 | 2 | 18 |
| Professional | 5 | 2 | 3 | 9 |
| Social | 3 | 20 | 1 | 21 |
| None | | 1 | 6 | 6 |
| Total Number of Codes | 36 | 41 | 37 | 114 |

Participants reported that the mental rotation activities, "Elevation" and "Common Landforms," was most-effective at getting them to think spatially (44% of codes), followed by spatial visualization activity, "Topographic Profiles," (40%), and then the spatial orientation activity, "Positioning Yourself in the Landscape," (16%). Participant-reported most improved skill was fairly evenly distributed, however, mental rotation had the lowest count for most-improved skill with 31% of codes. Spatial orientation was next with 33%, and spatial orientation followed with 36%.

## Discussion

There are many studies that employ the AR sandbox in the classroom to teach geological concepts, but there have not been any that aim to train spatial ability. The geosciences are inherently spatially intensive and may require a considerable amount of spatial ability to be successful in coursework and beyond (Kastens et al., 2009; Gold et al., 2018). One of the goals of this study was to assess the spatial ability of the undergraduate population at a large southeastern U.S. university using the SRI to determine if STEM and non-STEM students performed differently. STEM students significantly outperformed non-STEM students on the SRI, confirming what other studies have found with other instruments (Wai et al., 2009). Using the AR sandbox, we hoped to see significant improvement after engagement with the intervention. Although we did see post-intervention gains, both the experimental and control groups' scores improved on the SRI from pre- to post-assessment. This could be largely due to the practice effect, where participants acknowledged that they remembered the assessment and were aware of answering differently and more confidently on their second attempt. This may point to the fact that practice is an essential component of developing spatial skills (Ormand et al., 2014). As such, this simple re-exposure to the SRI assessment, combined with likely more attention by research subjects the second time they took the test (since the second deployment was in the lab versus the first exposure was on their own outside of lab) improved both experimental and control groups' scores.

Participants found spatial visualization to be the most challenging skill and participants had the least amount of strategies to solve spatial visualization problems. While there is not a generally agreed upon definition of spatial visualization, this skill can be very cognitively demanding as there are steps of mental manipulation that one must undergo (Salthouse et al., 1990). The initial assessment also showed that the mean score for the spatial visualization performance was the lowest among the skills. Students also had a harder time describing applications of this skill.

While spatial orientation was notably perceived as easier than the other spatial skills by participants, mental rotation was similar to spatial visualization in perceived difficulty. Mental rotation had the lowest report of improvement by participants and a high number of challenges were associated with the skill. Participants also reported having few strategies for solving mental rotation problems. However, the mental rotation activities were those that participants found most effective at training their spatial ability, which points to potential of the AR sandbox effectively supporting spatial skills in future work.

Spatial orientation was easier for participants and, as such, they had a higher number of strategies they employed, which suggests that they are likely getting more practice in spatial orientation compared to mental rotation and spatial visualization. Tartre (1990) discusses that spatial orientation does not require manipulation of the object itself, only changing the perspective from which someone views the object, which may explain the relative ease, as students had a higher mean score for the spatial orientation skill on the initial assessment. The primary strategy participants identified for spatial orientation challenges was perspective-taking. Participants also found the spatial orientation activity to be least effective at training spatial ability likely due to the participants' already high spatial orientation ability, indicating that the AR table has lowest potential to effectively support students with developing this skill.

The results of this study indicate that students have a difficult time with mental rotation and spatial visualization, but they perceive activities that use the AR sandbox to train these spatial skills to be very effective. Furthermore, since students have little experience with these skills, they perceive that they have improved just from being exposed to the skill via the AR sandbox. Participants also responded positively to tasks that involved creating a landscape after imagining and hypothesizing what the landscape will look like after some manipulation, whether that be rotating or viewing a feature in profile view. Since students lack strategies to be successful in solving complex spatial challenges, such as spatial visualization, AR activities that embed spatial training have potential to increase students' spatial ability.

## Conclusions

We hypothesized that there was a significant difference between STEM and non-STEM performance on the SRI and our hypothesis was supported. STEM participants significantly outperformed their non-STEM counterparts. We hypothesized that the developed AR sandbox activities would improve the spatial thinking ability of low performers. The difference in scores from pre-post assessment for spatial orientation and rotation skills were significant for both the experiment and control groups indicating that there may be a large practice effect, where re-exposure to the spatial assessments provided both groups additional practice, allowing for improvement regardless of AR table exposure. However, spatial visualization did not see this statistical effect where participants found spatial visualization to be the most difficult spatial skill to perform and they had the fewest number of strategies for solving spatial visualization problems. As such, this research shows that spatial visualization may have the greatest opportunity to improve. The AR table should continue to be tested as such AR supported training may benefit students as they create strategies to solve spatial visualization problems.

## Future Research Recommendations

The activity for the AR sandbox needs to be retooled, as it may not be helping students improve their overall spatial ability in this setting, or it may need to focus purely on developing spatial visualization skills in future iterations. Once the activities are redesigned, we recommend that researchers document what strategies are employed by students when they use the sandbox based on the insights provided by this exploratory research combined with video documentation and think-aloud interviews, as this may give more insight about how best to use the AR sandbox to support student spatial visualization skills. We also suggest that future experiments have students return to the lab or classroom setting multiple times, getting multiple exposures to the AR sandbox while conducting targeted activities designed to support spatial visualization skills. Finally, to address the re-test effect with spatial thinking ability we suggest either employing different spatial visualization tests at the different re-test times or space the re-test time farther out from the initial test to minimize student recall of the problems. We also suggest future work focus on an eye-tracking study of students solving spatial visualization problems on the spatial assessment pre- and post-exposure to the AR table, where data from eye-tracking can be combined with the strategies students report in order to more fully understand what students are doing when they solve these problems. Further, we suggest examining what high performers/experts do during the same spatial visualization tasks in order to compare which strategies are most effective. After identifying expert strategies, the activities can be further refined to give students the tools they need to solve spatial tasks. Lastly, we suggest more in-depth analysis of the pre-test survey data collected in this study where the data are inspected for differences between specific STEM and non-STEM majors and gender for each spatial skill tested.

## Significance

Currently, educational systems and academic institutions do not train spatial skills nearly enough to address the disparity in the distribution of spatial skills in a student population (Kastens et al., 2009). However, spatially rigorous geoscience courses have been shown to develop and enhance spatial tasks not exclusive to the geosciences (Kastens et al., 2009). This research could promote the AR sandbox as a viable teaching tool to be used in curriculum building for undergraduate geoscience classrooms. The AR sandbox has the potential to improve multiple spatial skills, and being exposed to the AR sandbox in an introductory geoscience course could help students be better equipped to solve spatial problems that present themselves in the STEM domains.

The results of this research can be extended to K-12 teaching and learning settings. Long-term goals in the geocognition area of research could begin to address the gap in base spatial visualization between women and men and increase retention in the STEM fields by developing these skills at a time in the learning process where other essential skills are being cultivated.

The AR sandbox has the potential to increase spatial skill development of future majors that are not yet currently choosing the geosciences as their field of study but may be enrolled in an introductory geoscience course.  Geosciences is currently one of the least ethnically and racially diverse fields among STEM disciplines (Baber et al., 2010). However, introductory courses often have a diversity of students enrolled since these course often serve as core science requirements at most universities. As such, the results of this research could support using the AR sandbox in introductory courses, helping to develop student spatial thinking skills in the context of geology, and potentially leading to greater participation from underrepresented groups in the geosciences.

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Appendix A. AR sandbox activities

Name
Date

# Spatial Thinking

Spatial thinking, simply put, is *how we think about objects in space and all the ways we can transform and manipulate those objects mentally*. Research has shown that science, technology, engineering, and math (STEM) students are successful in those fields because, on average, they have greater spatial thinking ability than their non-STEM counterparts. Thankfully, spatial thinking can be improved!

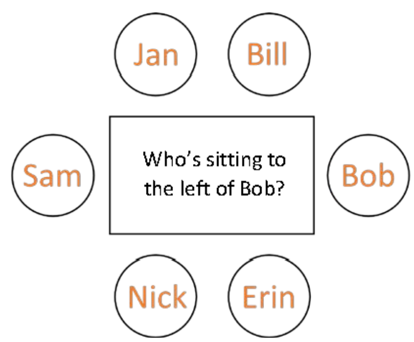
The activity you will be doing today involves using three spatial skills to complete an introductory geology exercise: mental rotation, spatial orientation, and spatial visualization.

Mental rotation involves turning an object about an axis.

What direction was this word rotated?


---

Spatial orientation involves understanding perspective and how one object relates to a frame of reference.

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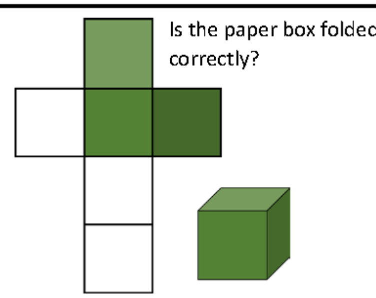
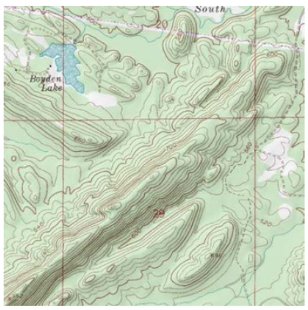
Spatial visualization involves any multi-step mental manipulation of an object to complete a task.



## Topography

Topography is the *physical shape of a landscape*. It includes how high or low, how wide, and how deep or thick landforms within the landscape are. To document the topography of landscapes, geoscientists use topographic maps that use lines to mark areas of the same elevation. With this topographic information, we can determine how water moves about the landscape or the relative height of landforms in the landscape, to name a few.



As you can see from the 2-dimensional topographic map to the left, it may be difficult to understand what these features may look like in 3-dimensions. That's where the augmented-reality (AR) sandbox is here to help! Using this technology, we can recreate this two-dimensional topographic map to explore the landscape in 3-dimensions.  In this activity, you will be asked to work through this worksheet, complete written answers, and work in the AR sandbox,

When geosciences are working with maps and landscapes, they need to use spatial skills much like the ones mentioned earlier.  This activity will use mental rotation, spatial orientation, and spatial visualization.

### What you'll DO

1. Recreate landscapes from topographic maps in the AR sandbox.
2. Identify common landforms.
3. Orient yourself in the landscape to identify features using cardinal and relative directions.
4. Sketch the landscapes you create in the sandbox in 2-D and 3-D.

### What you'll LEARN

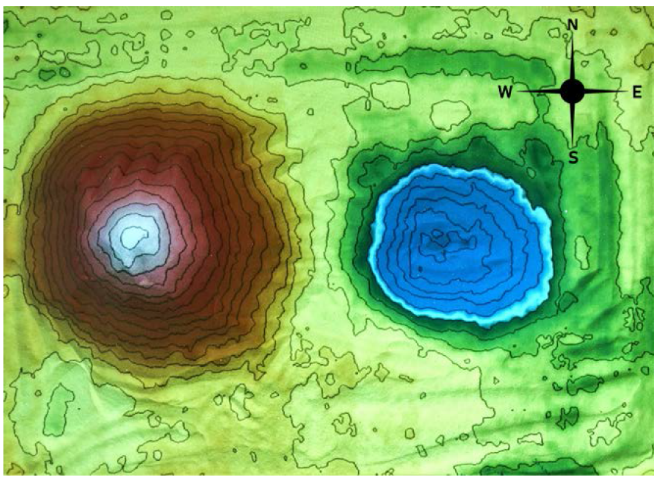
1. How to use colors and numbers to represent elevation.
2. How to identify the characteristics of watersheds.
3. How to interpret steepness of slope.
4. How to spatially represent landscapes in 2-D and 3-D.
5. How to use cardinal and relative directions to give and receive instructions.

## Let's get started!

### Elevation

Elevation is *the height of a landform relative to a fixed point*. The way we measure elevation is by comparing it to sea level, which is universally measured as 0 ft. On a topographic map we can depict elevation using colors and numbers.

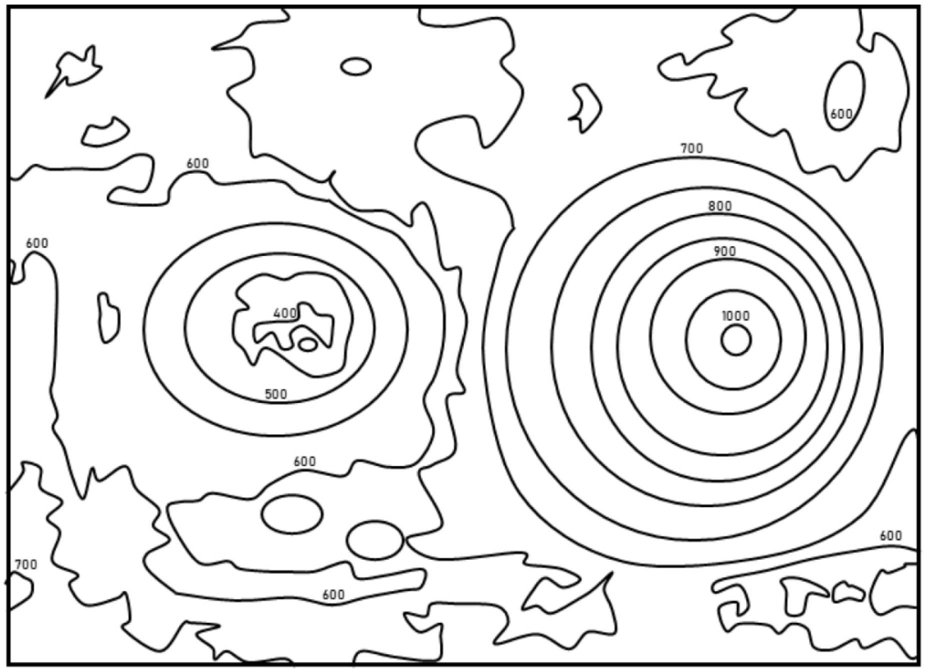
For example, the topographic map below was made in the AR sandbox. Take a second to **write** your predictions about what point on the map is the highest and what point is the lowest.




**Recreate** this map (above) in the sandbox, and try to match the colors in the sandbox to the ones on the map. Were your predictions correct?

So, how do the colors represent elevation, e.g. is green higher than red? Is yellow lower than blue? How do you know?

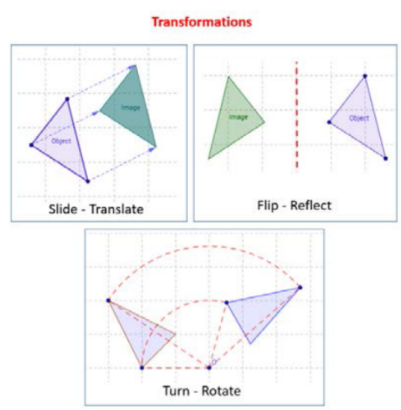
Examine the map below. Does it look familiar? Instead of colors, this map has numbers representing elevation. **Mark** the areas with the highest elevation and the lowest elevation.




**Compare** this numbered topographic map to the colorful topographic map. What happened to the map to achieve this new position?

A. Rotation
B. Flip
C. Translation

Remember: Mental rotation involves being able to turn an object, or map in this case, and reproduce maps from that rotation.

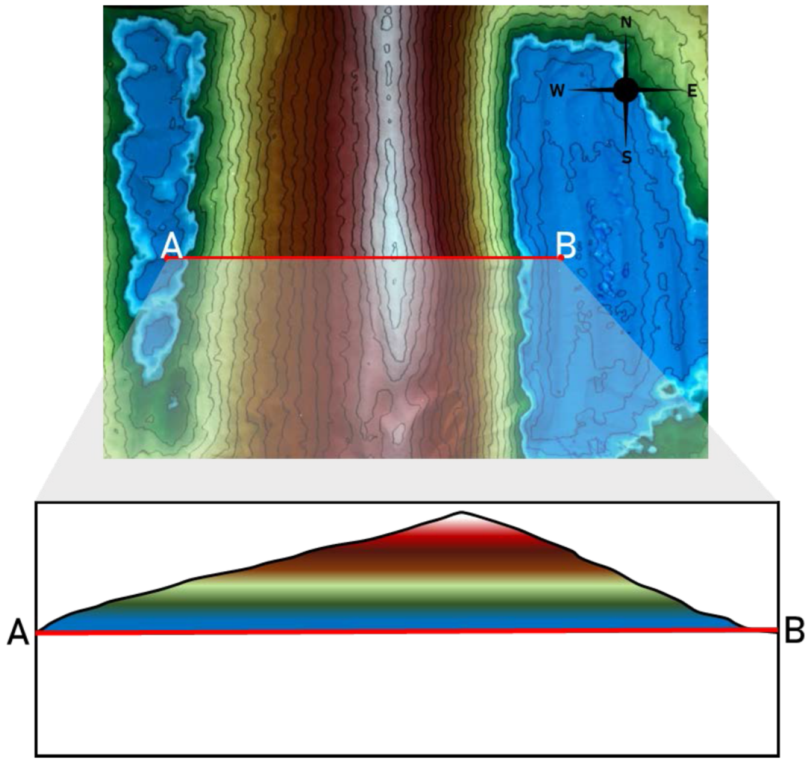



Based on the original colorful map on the previous page, d**raw** a compass on the numbered map above indicating which way is now North, South, East, and West.

## Topographic Profiles

Topographic profiles are *cross-sectional views of landscapes*. Cross-sections can show us how relatively tall, wide, and steep a landform is from the side. Taking a cross-section looks like we're cutting into the landscape to see its profile.

For instance, look at the topographic profile of a ridge, an elongated, narrow hill, in the below image. The cross-section, A-B, goes from West to East.



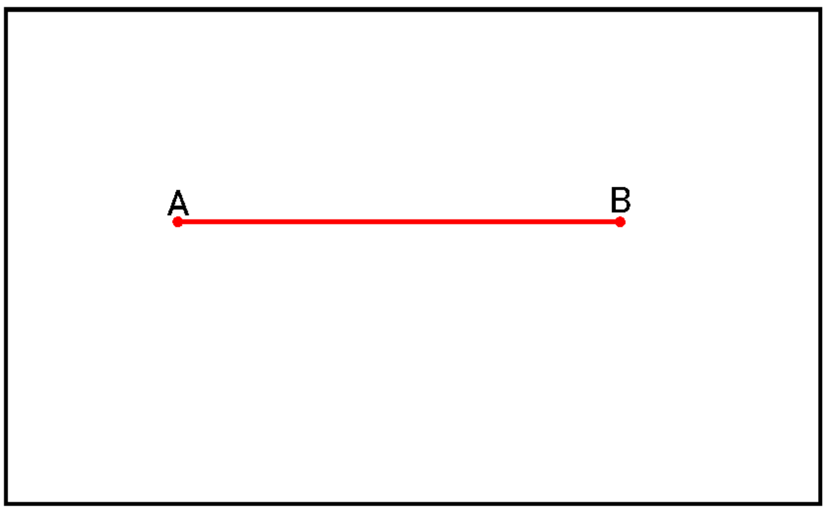

Take a note of the topographic profile above. **Mark** the steeper side of the ridge with a check. Notice the *spacing* between the lines. How is the spacing different for steeper slopes and shallower slopes?

**Recreate** this map in the sandbox using what you determined the line spacing to mean about steepness of slope.

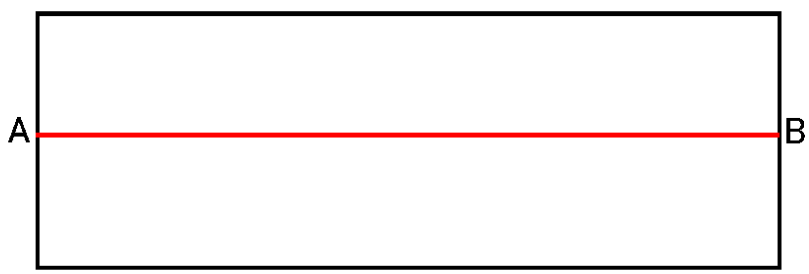
## Topographic Profiles

This activity involves spatial visualization, which is using multiple mental skills to solve a spatial problem.

**Create** your own landscape in the sandbox by first drawing a compass to mark the cardinal directions, and then sketching your landscape in the box below. To help start you out, **make** a lake in the northeast corner of the sandbox.



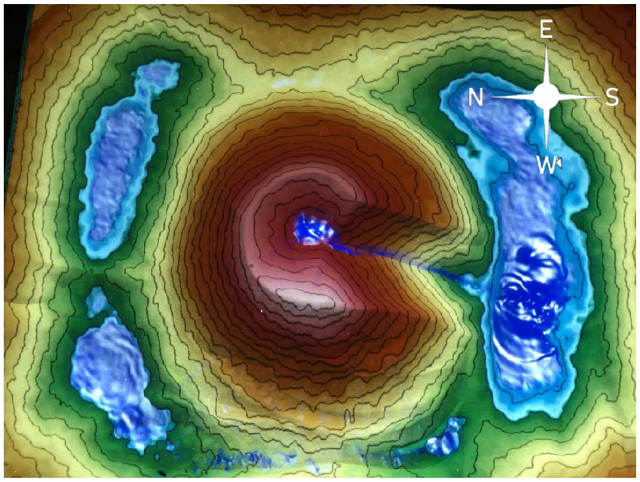

Roughly **sketch** what the topographic profile of this cross-section of your landscape from A to B would look like. Refer to the previous page for help sketching your profile. **Write** what direction your cross-section is in.




**Reflect** and **write** on how you were able to create your topographic profile.

## Common Landforms

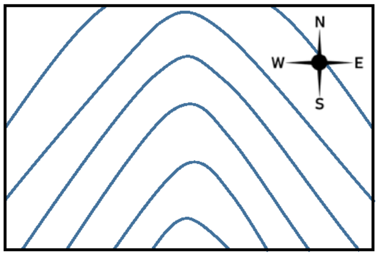
There are common landforms that are identifiable on maps, like river channels and ridges. We've already seen an example of a ridge on a landscape. Let's take a look at how to identify a river channel.

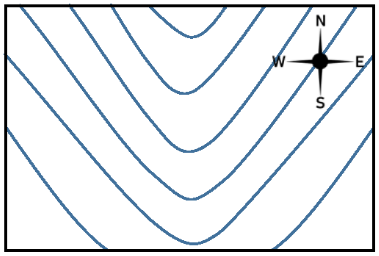



In the map above, we see a conical volcano with lakes in its central crater, to the south at the base of it, and two to the north. Let's investigate the features of the landscape by **creating** this map in the sandbox. (Tip: Build the volcano first before carving your river).

**Write** what the contour lines look like at the river channel, *a landform that allows for a narrow body of water to travel from high areas to low*, extending from the top of the mountain to the lake to the south? (Tip: To make it rain in the sandbox, stretch your hand out over where you want it to rain.)

**Draw** an arrow on each of the diagrams below indicating which direction the water is flowing.

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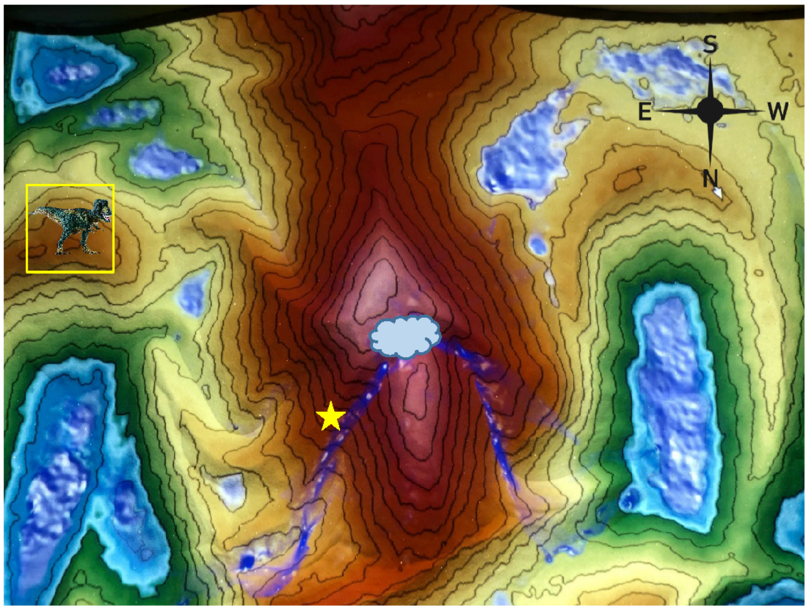
## Positioning Yourself in the Landscape

**Recreate** this landscape in the sandbox with the North direction facing the wall. Grab a dinosaur from the container below, and place it on the hill on the East side of the map. That dinosaur is you! This activity involves spatial orientation where you have to make decisions about where things are related to each other in space.




If you, the dinosaur, traveled west to get to the good watering hole, what feature would impede your journey?

A. A deep lake
B. A ridge
C. A glacier

**Write** which direction is the river traveling where it is marked with a star? The cloud is marking where it has just rained. (Tip: To make it rain in the sandbox, stretch your hand out over the area where the cloud is.)

Thank you for completing this activity!

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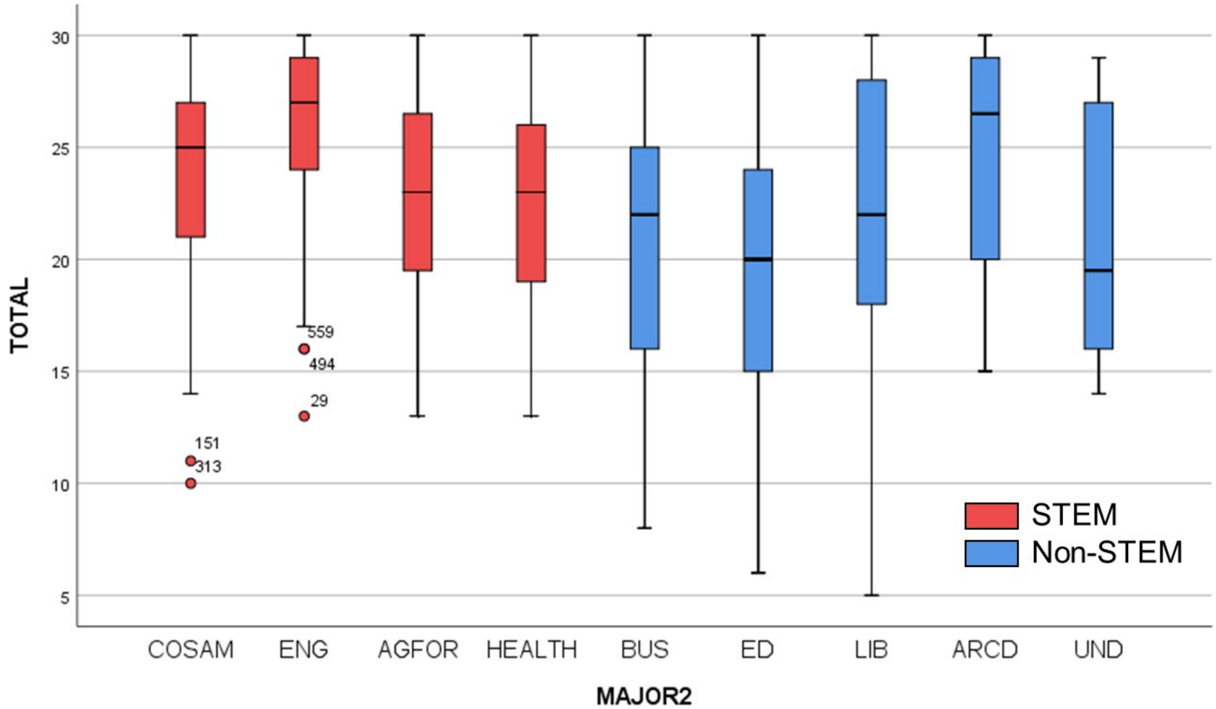
Appendix B. Distribution of spatial ability by major.




*Descriptive Statistics by Major*

| Major | | N | M | Std. Dev. |
|---|---|---|---|---|
| COSAM | Science and Mathematics | 135 | 23.82 | 4.207 |
| ENG | Engineering | 79 | 25.92 | 3.876 |
| AGFOR | Agriculture, Forestry, and Animal/Veterinary Sciences | 27 | 22.93 | 4.402 |
| HEALTH | Pre-Professional Health and Human Sciences | 48 | 22.23 | 4.502 |
| BUS | Business, Marketing, and Economics | 105 | 20.58 | 5.764 |
| ED | Education | 65 | 19.49 | 5.826 |
| LIB | Liberal Arts and Psychology | 69 | 21.57 | 6.316 |
| ARCD | Architecture, Design, and Building Science | 22 | 24.14 | 5.462 |
| UND | Undeclared | 10 | 21.00 | 5.793 |
| Total | | 560 | 22.51 | 5.442 |