Google Earth Mapping Exercises for Structural Geology Students—A Promising Intervention for Improving Penetrative Visualization Ability

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ABSTRACT

Three-dimensional thinking skills are extremely useful for geoscientists, and at the undergraduate level, these skills are often emphasized in structural geology courses. Google Earth is a powerful tool for visualizing the three-dimensional nature of data collected on the surface of Earth. The results of a 5 y pre- and posttest study of the three-dimensional visualization abilities of undergraduate students ($N = 75$) enrolled in a structural geology class at a small, liberal arts college are presented. The data suggest students achieved statistically significant gains in three-dimensional visualization skills over the course of the semester. Mean pretest scores for female students tended to be lower than those of male students. This gender gap, however, was no longer statistically significant in the posttest scores, with female students showing higher average gains in spatial skills compared to their male counterparts. These data show a correlation between the introduction of Google Earth map interpretation exercises, available on the Science Education Resource Center's Web site and developed by Tewksbury, and improved student visual penetrative thinking ability. Results support the hypothesis that individuals with greater contextual knowledge are able to more successfully circumvent lower three-dimensional spatial visualization ability. The exercise appears to be most effective in improving penetrative visualization ability for those students who have sufficient background knowledge. Those with less geological knowledge appear to benefit less from the Google Earth–based intervention studied here. © *2015 National Association of Geoscience Teachers*. [DOI: 10.5408/13-108.1]

Key words: Google Earth, spatial visualization, visual penetrative ability, contextual knowledge

INTRODUCTION

Three-dimensional thinking skills are widely recognized to be of critical importance to geoscientists and therefore have been the subject of a wide variety of studies seeking to improve teaching and learning of spatial skills (e.g., Kali and Orion, 1996; Reynolds et al., 2006; Titus and Horsman, 2009; Ormand et al., 2014). Surveys of three-dimensional thinking skills clearly demonstrate that some students are better than others (Lord, 1985; Kali and Orion, 1996; Piburn et al., 2002) and that these skills can be improved with appropriate interventions (e.g., Lord 1985; Uttal and Cohen, 2012; Uttal et al., 2013). For example, Sorby and Baartmans (2000) developed a 10 week training program for freshman engineering majors focused on improvement of spatial visualization skills. Over a 6 y period, students that completed this program consistently improved their visualization skills, were more likely to stay in the major, and finished the major in less time. On a different scale, Terlecki et al. (2008) engaged students in playing *Tetris* on a regular basis, which improved their ability to do three-dimensional mental rotation. These are two examples of how well-conceived interventions can improve student spatial visualization skills.

There is high degree of interest in the geoscience community in improving our quantitative understanding of the relative efficacy of different interventions for improving three-dimensional visualization skills (e.g., Piburn et al., 2005; Kastens and Ishikawa, 2006; Reynolds et al., 2006; Titus and Horsman, 2009; Ormand et al., 2014). Geoscience majors display a wide range of spatial visualization abilities (Ormand et al., 2014); therefore, successful teaching strategies must effectively address this range in ability. Google Earth is commonly used in both teaching and research (e.g., Tewksbury, 2008; Whitmeyer et al., 2010) and is one potential tool for improving visualization skills in students. In 2011, the Geological Society of America held a Penrose Conference at Google headquarters with the specific goal of more broadly distributing Google Earth–based education materials. The various viewpoints available in Google Earth, varying from a bird's-eye view to an oblique perspective view, afford users the opportunity to engage data sets from numerous perspectives (e.g., Tewksbury, 2010; SERC, 2015). It is well documented that many students have difficulty visualizing the three-dimensional structure of a region based solely on looking at a geologic map and cross section (Piburn et al., 2002; Kastens and Ishikawa, 2006). Google Earth is potentially a powerful tool for bridging the cognitive gap between a two-dimensional geologic map and a two-dimensional cross section (Whitmeyer et al., 2010).

Barbara Tewksbury (Hamilton College) developed and posted on the Science Education Resource Center's (SERC) On the Cutting Edge Web site a series of Google Earth exercises for undergraduate structural geology students (Tewksbury, 2008, 2010, 2011; SERC, 2015). The exercises were designed to have students "discover" the concepts of contacts, strike, and dip by engaging in mapping and cross-section construction exercises based in Google Earth. Using these exercises, students work with inclined contacts exposed in arid regions of the world (e.g., Utah; Fig. 1). The lack of vegetation in arid regions makes it possible to construct a geologic map using the aerial photo imagery available in Google Earth. The ability to change perspective

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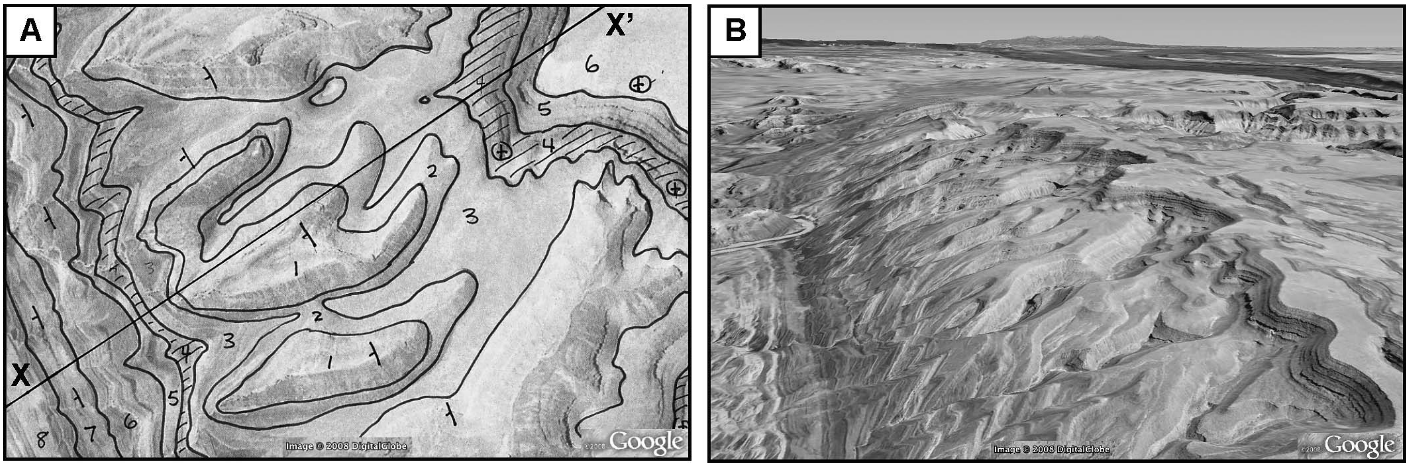

FIGURE 1: (A) Bird’s-eye view geologic map of the Raplee Anticline near Mexican Hat, UT. Contact lines are drawn over Google Earth imagery, and units are numbered from oldest (1) to youngest (8). The line X-X’ marks the orientation of the cross section drawn by students. (B) The folded nature of the rocks is readily apparent in an oblique view of the same structure in Google Earth. Both images are from Tewksbury (SERC, 2015).

from map view to oblique view provides students an opportunity to dynamically engage the three-dimensional relationship between contacts on a geologic map and the topography.

This study presents the results of a 5 y pretest/posttest survey of the spatial visualization skills of students enrolled in an undergraduate structural geology course. The data suggest that using Google Earth correlates with increased student visual penetrative ability, but these gains are apparently limited to those students with sufficient geologic knowledge to take advantage of the exercises.

METHODOLOGY

Study Population and Design

The study took place between 2007 and 2011 in a structural geology course at an undergraduate, liberal arts college populated by approximately 5,000 students mostly ranging from 18 to 21 y old with an average SAT score of 1329 for students enrolled during the study period. Approximately 15%–20% of the student body during this time period self-identified as an ethnic minority, while approximately 5%–10% of geology majors identified as minorities. The student body was 58% female and 42% male, and the study group was almost evenly split between male and female students (37 female, 38 male). All majors were required to take structural geology, which is a 300-level course intended for juniors and seniors. Most students took at least four required geology classes prior to taking the structural geology course (physical, historical, mineralogy, petrology). Students who chose to take the class as seniors had also completed two or three additional required courses (paleontology, stratigraphy, and/or geomorphology).

Tewksbury’s Google Earth exercises were introduced into the structural geology class starting in 2009. Subdivision of the study population is therefore based on year of enrollment rather than random assignment. Those students enrolled in structural geology in 2007 and 2008 were used as baseline to gauge the effect of the Google Earth exercises in 2009–2011. The lack of a random assignment of students to either a control group (pre–Google Earth) or an experimental group (post–Google Earth) makes this research nonexperimental in design (e.g., Shadish et al., 2002). Students’ baseline three-dimensional visualization abilities were measured on the first day (pretest) and last day (posttest) of class using the visualization exam assembled by Titus and Horsman (2009). The goal of this study was to test the hypothesis that implementation of Tewksbury’s Google Earth exercises improves students’ three-dimensional visualization skills.

Google Earth Intervention

The exercises designed by Tewksbury (SERC, 2015) are subdivided into four main modules: inclined contacts, strike and dip, horizontal and vertical contacts, and mapping folded rock. Students begin by working on one limb of a fold, i.e., a region with inclined contacts. After developing a map, determining dip directions, and constructing a cross section, students are then introduced to the concepts of strike and dip. Next, Tewksbury introduces the outcrop patterns for horizontal and vertical contacts. In the final stages of the exercise, students develop a map and cross section through an area of folded rock (Fig. 1).

In my experience, full implementation of Tewksbury’s protocol took 2 to 3 weeks of class time, including lecture and laboratory. I deployed three of the four modules (excluding the horizontal and vertical contact module) and had my students finish by constructing a map and cross section of the Raplee Anticline near Mexican Hat, UT (Fig. 1). Anecdotally, this exercise was extremely satisfying. Students seemed to grasp the concepts of contacts, the rule of v’s, strike and dip, and cross-section construction more naturally.

Data Collection

Three tests of spatial thinking skills were given as pre- and posttests to students enrolled in the structural geology course. Students were required to take both the pre- and posttest, but they were graded solely on participation. Administration of the tests followed Titus and Horsman (2009), where students were given 3 min to complete each section of the test. Correct answers earned one point, and, in

TABLE I: 3D visualization exam results by year.[1]

	Spatial Relations	Spatial Manipulations	Visual Penetrative Ability	Total
Fall 2007 (N = 10; F = 6, M = 4)				
Pretest	3.7 (1.7)	13.7 (4.1)	5.7 (2.4)	23.1 (5.5)
Posttest	4.7 (2.3)	14.5 (6.0)	5.0 (2.9)	24.2 (8.3)
Gain	1.1	0.7	−0.7	1.1
Fall 2008 (N = 14; F = 3, M = 11)				
Pretest	4.4 (3.0)	14.8 (5.8)	5.8 (1.7)	25.0 (8.2)
Posttest	4.6 (3.0)	16.8 (3.6)	5.5 (3.1)	26.9 (8.4)
Gain	0.2	2.0	−0.3	1.9
Fall 2009 (N = 15; F = 11, M = 4)				
Pretest	3.7 (1.7)	12.7 (4.6)	4.9 (2.9)	21.2 (6.7)
Posttest	4.5 (2.5)	14.9 (5.0)	6.0 (2.8)	25.4 (8.1)
Gain	0.8	2.2	1.2	4.2
Fall 2010 (N = 14; F = 5, M = 9)				
Pretest	4.0 (1.7)	11.6 (6.2)	4.6 (2.5)	20.2 (8.4)
Posttest	4.8 (3.3)	12.8 (5.4)	6.0 (3.2)	23.6 (10.1)
Gain	0.8	1.2	1.4	3.4
Fall 2011 (N = 22; F = 12, M = 10)				
Pretest	4.2 (2.1)	11.8 (6.1)	5.5 (3.2)	21.5 (9.4)
Posttest	4.6 (2.2)	13.4 (6.3)	7.8 (4.1)	25.8 (10.1)
Gain	0.4	1.6	2.3	4.3

[1]All scores are presented as mean (one standard deviation); pretest and posttest scores give the mean score out of 10, 20, 15, and 45, respectively, for each test; gain = mean posttest − mean pretest; N = total number of students; F = number of female students; M = number of male students.

an effort to discourage guessing, incorrect answers resulted in loss of a quarter of a point. Unanswered questions received a score of zero.

The three tests administered were assembled by Titus and Horsman (2009) and have been used in previous investigations of spatial thinking in the geosciences (Titus and Horsman, 2009; Ormand et al., 2014). Each test targeted a different category of spatial thinking ability: spatial relations, spatial manipulations, and visual penetrative ability (Titus and Horsman, 2009). The spatial relations portion of the assessment was drawn from the Purdue Visualization of Rotations Test (PVRT; Guay, 1976). This subtest measures the ability to rotate an object about its center. The spatial manipulation portion examines the ability to mentally rearrange an object into a different configuration with questions drawn from the Educational Testing Service (Ekstrom et al., 1976). Lastly, penetrative visualization involves the ability to mentally envision the inside of a solid object (Kali and Orion, 1996; Titus and Horsman, 2009). This ability is tested with the Planes of Reference Test (Ormand et al., 2014) using questions developed by Crawford and Burnham (1946), Myers (1953), and Titus and Horsman (2009). Traditionally, the ability of a student to draw an appropriate cross section is used to assess the accuracy of the three-dimensional model of a map area. Therefore, Google Earth exercises should improve students' three-dimensional penetrative visualization ability.

Student grades in prior geology courses were gathered from their transcripts to assess variation in baseline geological knowledge. A contextual knowledge score was calculated using seven required classes (noted above) that all geology majors must complete. The score factored in both the number of classes taken and student performance. For each class taken, the student earned up to four points depending on his or her grade following a standard four-point grading scale (i.e., A = 4, A− = 3.7, etc.). A student with "A's" in all seven classes prior to structure earned a score of 28 (i.e., 7 × 4). The "average" student earned a score of 12, i.e., four classes with a B in each class (4 × 3).

Data Analysis

The data collected were subjected to a standard statistical analysis to address the following questions: (1) Do the Google Earth exercises developed by Tewksbury (SERC, 2015) improve students' spatial thinking skills? (2) Are these effects evenly distributed across students with different levels of background knowledge in geology?

The study group was subdivided into subgroups based on whether or not they took part in the Google Earth exercises and their level of background geologic knowledge. For each subgroup within the study, the following values were calculated using Microsoft Excel:

- mean pretest and posttest scores for each of the three visualization tests;
- mean gain (mean posttest minus mean pretest);
- p-value, using a paired, two-tailed t-test, of pretest scores versus posttest scores; and
- p-value, using an unpaired, two-tailed t-test, of posttest scores for the pre–Google Earth group versus the post–Google Earth group.
- All populations analyzed with the t-test passed the Kolmogorov-Smirnov test for a normal distribution.

RESULTS

Over a 5 y period, students improved their spatial visualization test scores while enrolled in the structural geology course (Tables I and II and Fig. 2). These gains were realized in all three categories of spatial thinking skills. On a year-by-year basis, the gains in spatial relations and spatial manipulations varied considerably (Table I). Pretest scores for male students were significantly better than those for female students. However, female students improved more than their male counterparts, and the difference between the posttest scores for male and female students was not significant at the 95% confidence level (Table II and Fig. 3).

In 2007 and 2008, students on average scored lower on their visual penetrative ability at the end of the structural geology course compared to the beginning (Table I). Recall that the visual penetrative ability test measures students' skill at mentally "cross-sectioning" an object. Drawing cross sections of deformed bodies of rock is a required skill within structural geology, which makes these negative scores particularly distressing. Introduction of the Google Earth exercises in 2009 correlated with a change in this trend (Table I and Fig. 4). Gains in visual penetrative ability increased ($p < 0.05$) after the introduction of the exercises. Those gains were maintained through the final 3 y of this study (Table I). These gains were most pronounced in

TABLE II: 3D visualization exam results by group.[1]

	Spatial Relations	Spatial Manipulations	Visual Penetrative Ability	Total
All (N = 75, F = 37, M = 38)				
Pretest	4.0 (2.1)	12.8 (5.5)	5.3 (2.7)	22.1 (8.0)
Posttest	4.6 (2.6)	14.4 (5.4)	6.3 (3.4)	25.3 (9.0)
Gain	0.6	1.6	1.0	3.2
p-value	<0.05	<0.05	<0.05	<0.05
Female (N = 37)				
Pretest	3.4 (1.8)	11.9 (5.8)	4.7 (2.5)	20.0 (8.1)
Posttest	4.0 (2.5)	13.7 (6.2)	5.8 (3.4)	23.5 (9.7)
Gain	0.6	1.8	1.1	3.5
p-value	0.13	<0.05	0.05	<0.05
Male (N = 38)				
Pretest	4.6 (2.2)	13.6 (5.1)	5.9 (2.7)	24.1 (7.5)
Posttest	5.3 (2.6)	15.0 (4.5)	6.8 (3.4)	27.0 (8.0)
Gain	0.7	1.4	0.8	2.9
p-value	0.05	<0.05	0.05	<0.05
Pre–Google Earth (N = 24, F = 9, M = 15)				
Pretest	4.1 (2.5)	14.3 (5.1)	5.8 (2.0)	24.2 (7.1)
Posttest	4.6 (2.7)	15.8 (4.8)	5.3 (3.0)	25.8 (8.3)
Gain	0.5	1.5	–0.5	1.6
p-value	0.19	0.07	0.45	0.20
Post–Google Earth (N = 51, F = 28, M = 23)				
Pretest	4.0 (1.9)	12.0 (5.6)	5.1 (2.9)	21.1 (8.3)
Posttest	4.6 (2.6)	13.7 (5.6)	6.8 (3.5)	25.1 (9.4)
Gain	0.6	1.7	1.7	4.0
p-value	<0.05	<0.05	<0.05	<0.05

[1]All scores are presented as mean (one standard deviation); pretest and posttest scores give the mean score out of 10, 20, 15, and 45, respectively, for each test; gain = mean posttest − mean pretest; p-value is the result of a paired two-tailed t-test comparing the pretest and posttest scores for each group; N = number of students; F = number of female students; M = number of male students.

students with average background knowledge or better (Table III and Fig. 5).

DISCUSSION

Structural geology at the study institution consists of many of the laboratory exercises typically associated with the class: three-point problems, calculation of strike and dip from a geologic map, stereonet analysis, cross-section construction, and map interpretation. Previous work (e.g., Lord, 1987; Titus and Horsman, 2009) suggests that spatial thinking skills can be improved with practice. This 5 y data set (Table I and Fig. 2) supports the hypothesis that exercises in a "traditional" structural geology curriculum generally improve students' three-dimensional visualization skills. Additionally, the pretest data (Fig. 3) support the widely accepted notion that male students tend to have higher spatial visualization skills than female students (e.g., Linn and Petersen, 1985). This gender gap, however, is no longer statistically significant in posttest scores (Fig. 3). Female gains tend to be higher than their male counterparts, but the difference in gains is not statistically significant. These data suggest that gender differences in spatial ability can be reduced through the practice involved in a "traditional" structural geology curriculum.

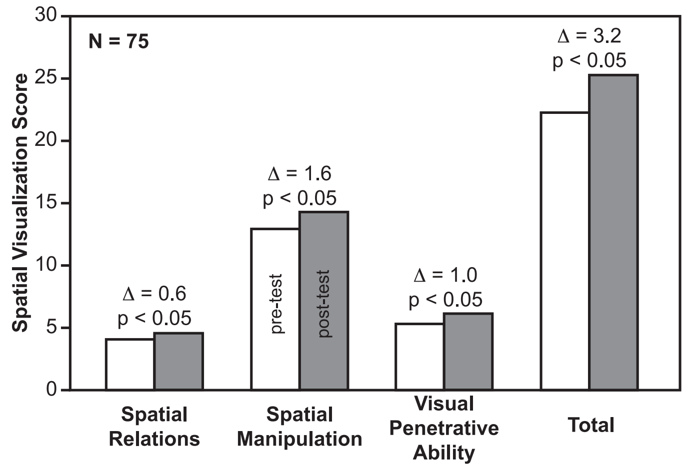

FIGURE 2: Aggregate spatial visualization test results from 2007–2011. Maximum scores for each portion of the test vary (spatial relations = 10, spatial manipulations = 20, visual penetrative ability = 15, total = 45). Mean gains (Δ) are the difference between the mean posttest and mean pretest scores. The p-values were calculated using a paired t-test with a two-tailed distribution. All gains are statistically significant at the 95% confidence level.

Although these results are promising, two potential shortcomings call these findings into question. First, previous work strongly suggests that simply taking a spatial test twice can lead to substantial gains (Titus and Horsman, 2009; Uttal and Cohen, 2012; Ormand et al., 2014).

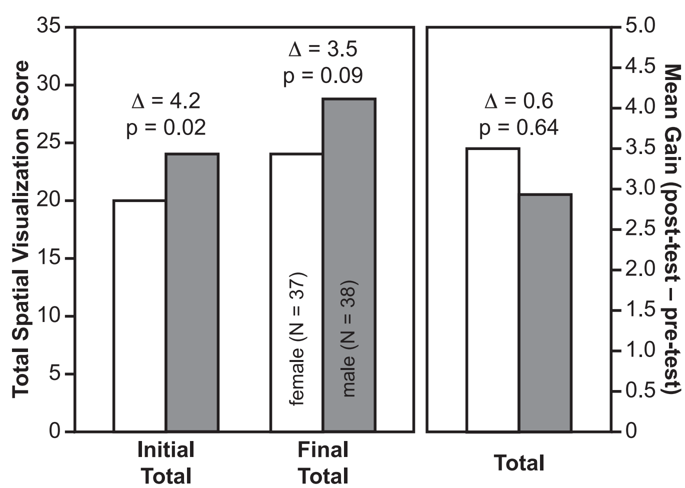

FIGURE 3: Pretest and posttest spatial visualization test results subdivided by gender. Maximum score for the entire test is 45 points. Mean gains (Δ) are the difference between the mean posttest and mean pretest scores. The p-values were calculated using a paired t-test with a two-tailed distribution.

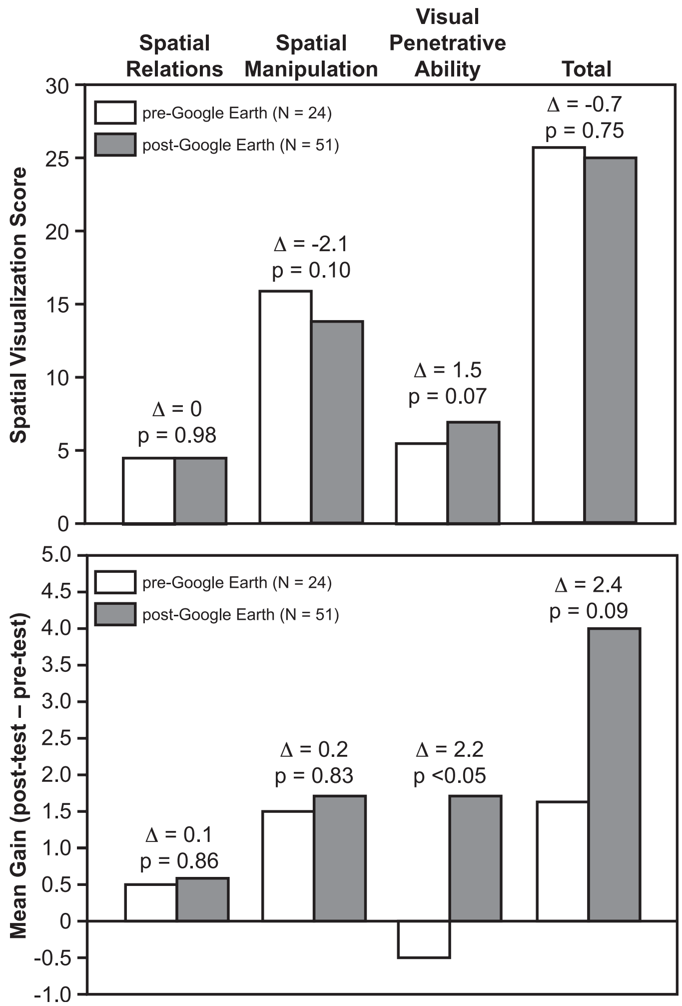

FIGURE 4: Comparison of final visualization test results and gains prior to (2008–2009) and after (2009–2011) the introduction of Google Earth exercises. Differences in pre– versus post–Google Earth scores are noted (Δ). The *p*-values were calculated using an unpaired *t*-test assuming a two-tailed distribution.

Therefore some of the gains observed in this data set are likely to arise from repeat testing and cannot be uniquely attributed to teaching interventions in the course. Second, the nonexperimental (e.g., Shadish et al., 2002) nature of this study means that the experimental and control groups were not randomly assigned. Students self-selected to join the study simply by becoming geology majors. Assignment to the pre–Google Earth versus post–Google Earth groups was based only on year of enrollment. The lack of random assignment indicates the possibility that some (or all) of the gains in three-dimensional visualization ability could be due to systematic differences between the pre– versus post–Google Earth groups. For example, studies show that general spatial thinking ability correlates with math SAT scores (e.g., Casey et al., 1995) and visual penetrative ability specifically (Cohen and Hegarty, 2012). Math SAT score data were not collected as part of this study; therefore, they cannot be ruled out as a potential cause of the observed gains. However, this is likely not the case given that the pretest scores for the post–Google Earth group were lower than those of the pre–Google Earth group (Table II).

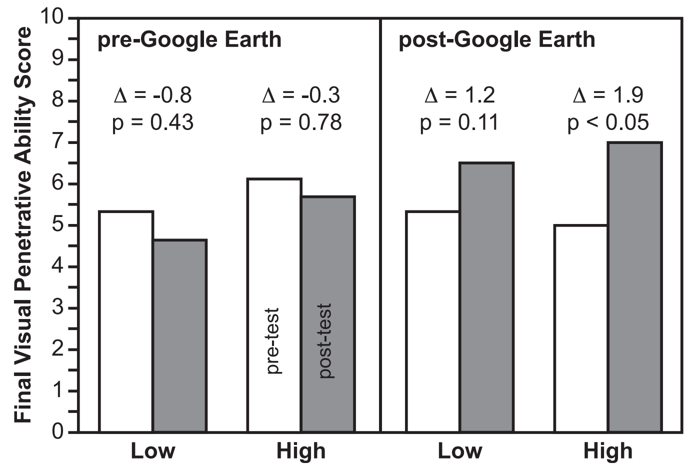

FIGURE 5: Gains in visual penetrative ability prior to and after the introduction of Google Earth exercises subdivided by contextual knowledge. The difference in pre- versus postintroduction mean gains is noted (Δ). The *p*-values were calculated using an unpaired *t*-test assuming a two-tailed distribution.

If we assume that gains arising from taking a spatial test twice are constant between groups taking the same test, then there is a correlation between the introduction of the Google Earth exercises and increased gains in spatial thinking skills (Table II and Fig. 4). While no clear changes in student gains in spatial relations and spatial manipulations were present, the data show an increase in visual penetrative ability (Table II). Disappointingly, student's penetrative ability scores dropped between the pre- and

TABLE III: Visual penetrative ability scores of pre– and post–Google Earth groups subdivided by contextual knowledge score.[1]

	Pre–Google Earth		Post–Google Earth	
	Low (<12) (N = 10, F = 4, M = 6)	High (≥12) (N = 14, F = 5, M = 9)	Low (<12) (N = 16, F = 8, M = 8)	High (≥12) (N = 35, F = 20, M = 15)
Prior knowledge	9.3 (1.4)	17.0 (3.2)	9.4 (3.0)	17.6 (3.9)
Pretest	5.4 (2.2)	6.1 (1.8)	5.3 (3.8)	5.0 (2.5)
Posttest	4.6 (3.1)	5.8 (2.8)	6.5 (4.0)	6.9 (3.4)
Gain	−0.8	−0.3	1.2	3.5
p-value	0.43	0.78	0.11	<0.05

[1]All scores are presented as mean (one standard deviation); N = number of students; F = number of female students; M = number of male students; prior knowledge = contextual knowledge score; pretest and posttest scores give the mean score out of 15; gain = mean posttest − mean pretest; p-value is the result of a two-tailed, paired t-test comparing the pre- versus posttest values for each group.

posttest in 2007 and 2008. Introduction of Google Earth–based exercises correlated with significantly ($p < 0.05$) improved student gains in this category (Fig. 4 and Table II). This module occupied 2 weeks of class (laboratory and lecture), so it represented a significant change to the curriculum. The exercises called on the ability of students to "see" the geologic structure hidden inside the three-dimensional terrane image displayed by Google Earth. Students were not asked to mentally rearrange images—e.g., restore a cross section to its initial, predeformation state—as part of this exercise. Similarly, students were not required to mentally rotate imagery. Therefore, it seems reasonable that introduction of the Google Earth exercises would impact visual penetrative ability scores but have no measureable effect on spatial relations or spatial manipulation abilities of students (Fig. 4).

Gains in visual penetrative ability, however, were not equally distributed across the population (Fig. 5). Students who began the class with greater geologic knowledge were better able to utilize the Google Earth exercises. There were no statistically significant gains in visual penetrative ability for those students with a limited geologic knowledge background (Fig. 5).

These results are consistent with prior published outcomes, which suggest that success in a spatially intensive field positively correlates to initial three-dimensional thinking ability primarily in novice students. Uttal and Cohen (2012) hypothesize that experts in science, technology, engineering, and mathematics (STEM) fields use mental depictions to solve problems without relying on their spatial visualization skills. Similarly, Hambrick et al. (2011) found a correlation between high spatial thinking skills and geologic mapping performance only for those with low levels of geologic knowledge. These authors suggest that geologists with high levels of geologic knowledge are able to find ways to work around limitations imposed by lower spatial visualization skills.

In both studies (Hambrick et al., 2011; Uttal and Cohen, 2012), increased contextual knowledge appeared to enable individuals to overcome lower three-dimensional visualization skills. The lack of statistically significant gains in the post–Google Earth, low-background-knowledge group in this study could be due to the inability of these students to use mental representations to solve problems. The first exercise required students to construct a geologic map of tilted beds. Hambrick et al. (2011) found that experts, when mapping a series of tilted beds, will call on their prior knowledge and test out a series of possible three-dimensional configurations, such as anticline, syncline, or tilted beds. The experts discarded models that did not fit the observations, anticline and syncline in this case, and kept the one(s) that worked (e.g., tilted beds). A mental representation of tilted beds was then used to imagine the area underground and construct an appropriate cross section. This process involves a lower cognitive load than mentally projecting each contact underground and attempting to assemble those projections into a geologically meaningful geometry. It is possible that students in this study with lower geologic knowledge were forced to devote more cognitive capacity to visualization than their peers with greater geologic knowledge.

Shipley et al. (2013) offered a complementary explanation for the split in low versus high geologic knowledge present in these data. While observing students on a structural geology field trip, Shipley et al. (2013) noted that more experienced geologists "filter" their observations to concentrate on the most meaningful information. For example, when tasked to sketch a cross-section of the Baraboo Syncline, an expert will focus on the orientation of bedding at an outcrop. Many outcrops in this region, however, also exhibit strong cleavage. To successfully construct a cross section, the cleavage orientations need to be distinguished from the bedding orientations. Experts have plenty of practice filtering their observations in this manner, while novices are forced to wade through a large volume of information in search of the most pertinent information. Google Earth exercises offer a similarly data-rich environment where the terrain can be observed from a variety of angles and orientations. While a student with greater geologic knowledge might seek out a strike-normal viewpoint, less experienced individuals may struggle to choose the most effective orientation to observe the structure.

CONCLUSIONS

Results of a 5 y pretest/posttest survey of junior- and senior-level undergraduates enrolled in a structural geology class suggest that implementation of Tewksbury's SERC teaching module "Teaching Geologic Map Interpretation Using Google Earth" correlates with increased gains in visual penetrative ability. Visual penetrative ability is directly related to the ability of students to mentally "cross-section" objects and, therefore, is a key skill to develop in future geologists. The data suggest that gains from the Google Earth exercises are most pronounced for students who have acquired sufficient geologic background knowledge. Students with less background knowledge may lack mental representations of deformed beds to help them understand the maps (e.g., Hambrick et al., 2011), and/or those students may be less efficient at filtering the data to find the most meaningful observations (Shipley et al., 2013). Regardless of the cause, students who are most vulnerable—i.e., those with limited background knowledge—also appear to be those least likely to benefit from a Google Earth exercise intervention.

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