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Spatial Ability Development in the Geosciences

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Abstract

We designed an experiment to evaluate change in students' spatial skills as a result of specific interventions. Our test subjects included high school students in earth science classes, college level non-science majors enrolled in large enrollment introductory geoscience courses and introductory level geoscience students. All students completed spatial tests to measure their ability to mentally rotate three-dimensional objects and to construct a three-dimensional object from a two-dimensional representation.

Results show a steady improvement in spatial skills for all groups. They also indicate that students choosing science majors typically have much higher spatial skills as they enter college. Specific interventions to improve spatial skills included having a subgroup of the non-science majors and high school students complete a suite of Geographic Information System (GIS) activities. The intervention at the high school level was more extensive and resulted in significant improvements in both categories of spatial ability. At the college level, the non-science majors that received the intervention showed no significant difference from those that did not, probably because the time spent on the intervention was too short. The geoscience majors had nearly three times the improvement of non-science majors in both categories of spatial ability attributed to hands-on weekly laboratory experiences. These results reveal a wide range of abilities among all groups of students, and suggest that we evaluate teaching strategies in all courses to ensure that students can interpret and understand the visual imagery used in lectures.

Spatial Ability Development in the Geosciences

Introduction

Courses in the geosciences have ambitious goals for teaching students about complex global processes. Instructors use images such as graphs and maps as tools to communicate geologic concepts and relationships. Then, students must mentally translate those graphs and maps to interpret complex processes that vary in space and time. Spatial abilities are used to mentally form, inspect, transform, and interpret images. Mathewson (1999) stated, ‘A spatial image preserves relationships among a complex set of ideas as a single chunk in working memory, increasing the amount of information that can be maintained in consciousness at a given moment.’ It is this integration of information that is critical in understanding complex geologic processes and patterns. To facilitate student success in the sciences, it is important to understand the spatial abilities of students and how well they can complete complex visual tasks.

To characterize the development of spatial ability, the following questions were considered.

- Does simple participation in a geoscience course improve spatial ability?
- Are there differences between male and female performance on tests of spatial ability?
- Are there instructional strategies that will develop students’ conceptual understanding of science and their spatial ability?

In particular, we investigated whether instruction with activities that use a geographic information system (GIS) would impact students’ spatial abilities. A GIS allows students to manipulate and interrogate two-, three- and four-dimensional visualizations in ways not possible with traditional maps, photographs and satellite imagery. Exploring spatial and temporal relationships in geologic data has the potential of developing spatial skills as students view both two- and three-dimensional representations of earth processes. For example, a GIS allows quantitative and visual searches and queries of spatial data sets, as well as changes in data symbolization and overlay of different data sets to reveal new relationships. A number of authors have proposed that a GIS could have an effect on students' conceptual understanding of science (Barstow, 1994; Salinger, 1994). Hall-Wallace and McAuliffe (2002) showed that conceptual understanding of science was improved by reinforcing concepts through discovery and problem solving with GIS-based activities, however the effect on improving spatial skills is not known.

Research on Spatial Abilities in Science and Engineering

A number of spatial abilities have been identified and defined by the mental processes used to solve different types of problems. At the extreme, spatial ability is divided into ten categories (Lohman, 1988), although more commonly three categories are used (McGee, 1979; Lohman, 1979; Pellegrino & Kail, 1982; Linn & Petersen, 1985; Pellegrino & Hunt, 1991; Voyer, Voyer & Bryden, 1995). To confuse matters, the title and definition of these categories often overlap among different research groups. In a meta-analysis of the literature, Linn and Peterson (1985) evaluated the cognitive rationale of tasks requiring spatial abilities and identified three main categories: spatial visualization, spatial perception, and mental rotation. Their schema for defining these skills is internally consistent and compares well with schema used by other researchers. However, these same categories have been called spatial visualization, spatial orientation, and spatial relations by others (Ekstrom, French, Hartman & Dermen, 1976; Lohman, 1979; Pellegrino & Kail, 1982; Pellegrino & Hunt, 1991). Still, there is considerable overlap in the definitions of spatial orientation and spatial visualization (Lohman, 1979), leading others (Pellegrino & Kail, 1982; Pellegrino & Hunt, 1991; Coleman & Gotch, 1998; Piburn et al., 2002) and us to consider only two main categories of spatial ability: spatial relations and spatial orientation.

Spatial relations is the ability to mentally rotate an object about its center (Shepard & Cooper, 1982). In the geosciences, this skill is used to evaluate crystal structures in mineralogy or to determine fault planes using a stereonet. Spatial orientation is the ability to mentally manipulate or transform an image or spatial pattern into another arrangement (Ekstrom et. al, 1976). For example, geoscience students must interpret a three-dimensional relationship such as a fault or fold represented on a two-dimensional map. Performance on measures of spatial ability has been correlated with performance in real world situations (Blade & Watson, 1955; Self & Golledge, 1994; Orion, Ben-Chaim & Kali, 1997; Travis & Lennon, 1997; Coleman & Gotch, 1998; Dabbs, Chang, Strong & Milun, 1998; Sorby, 2001; Hall-Wallace & McAuliffe, 2002). Therefore, we measured the development of students' spatial relations and spatial orientation skills in high school and at the introductory college level to quantify their preparation for and success in geoscience courses.

Spatial ability is important to success in the sciences and can be developed in students through instructional interventions (Blade & Watson, 1955; Lord, 1987; Kali & Orion, 1996; Orion et al., 1997; Travis & Lennon, 1997; Coleman & Gotch, 1998; Sorby, 2001; Piburn, 2002). Lord (1987) compared the spatial ability of science majors and non-science majors and found that successful completion of a science-involved discipline requires at least a modest level of spatial expertise. Lord (1987) also suggested that science educators should routinely include exercises that build and reinforce spatial thinking in their students. In Lord's study, students in a biology course completed a weekly half-hour exercise in which they imagined the bisection of a three-dimensional geometric solid and predicted the shape of the newly cut surface. At the conclusion of the semester, students who had completed the exercises were outperforming a control group on tests of spatial ability. Coleman and Gotch (1998) tested the spatial ability of chemistry students and found that their scores indicated prior student preparation in science, suggesting that these skills can be developed through the normal educational process. They suggested that instructors incorporate pedagogical techniques and exercises in the classroom that help students develop their mental imaging abilities. Kali and Orion (1996) investigated the specific characteristics of spatial ability required to perceive geologic structures by evaluating the performance of high school students on interpreting and resolving three-dimensional geologic structures. They identified visual penetration ability as a key skill for successfully solving these types of problems. According to Kali and Orion, visual penetration ability is the ability to mentally penetrate a structure. They suggested that providing students opportunities to disassemble physical models of geologic structures could improve their ability to perceive and mentally bisect geologic structures.

The need for a high level of spatial ability to be successful in the sciences is documented, but less is known about how much time and what types of exercises are required to develop these skills. Sorby (2001) designed and implemented a trimester course to improve spatial skills; students that worked with handheld objects and interactive computerized models four hours a week for ten weeks improved their scores on tests of spatial ability. Travis and Lennon (1997) used software that creates three-dimensional representations of mathematical concepts in a calculus course. They found that by the midpoint of the semester the students using the software scored higher on a test of spatial skills than students in a standard calculus course.

Recognizing the importance of spatial ability to success in the geosciences, Orion et al., (1997) looked for a relationship between introductory geology courses and spatial ability development. They found a positive relationship between studying earth science and spatial skill development, observing an improvement after one year. However, those students were enrolled simultaneously in a variety of science and mathematics courses, making it difficult to assess which experiences were impacting spatial ability. Blade and Watson (1955) evaluated the spatial skills of engineering students over the course of a degree program and found the most significant gains in ability were measured after the first year of study. First-year engineering students experienced three times the gain in spatial ability of non-engineering students. These gains were attributed to the hands-on technical nature of engineering coursework including courses in descriptive geometry, engineering drawing, and mathematics. These studies show that practice with three-dimensional representations can improve students' spatial abilities.

Sex differences must also be considered when evaluating spatial ability development. There is considerable debate in the literature about whether there are differences in spatial ability between males and females. A number of studies have shown measurable differences in spatial ability between males and females (Lord, 1987; Orion et al., 1997; Travis & Lennon, 1997; Coleman & Gotch, 1998). For example, Lord (1987) in a comparison of science and non-science majors, found that the spatial abilities of males were superior to the females in their respective groups, however, female science majors scored higher than male non-science majors. There have also been a number of studies where females had superior ability on certain spatial tasks, not allowing easy characterization of performance by gender (Linn & Petersen, 1985; Self, Gopal, Golledge, & Fenstermaker 1992; Dabbs et al., 1998). A study by Self et al. (1992) indicated that the gap in spatial ability was not present if the time limit on solving spatial problems was removed, and that often females have a higher level of accuracy. Sex differences in spatial ability, if they exist, could be addressed through instructional strategies and could impact recruitment and retention of future scientists.

Methods

Subjects

To address our research questions, we measured the change in spatial ability of a wide range of students studying the geosciences at the high school and introductory college levels. The subjects included 9-12 grade high school students enrolled in year-long earth science courses, first- and second-year college students enrolled in geoscience courses for non-science majors, and first- and second-year college students enrolled in introductory courses for geoscience majors. Using test and control groups, we were able to compare development of spatial skills between high school and college age students who completed GIS activities as part of their instruction and those who did not. In addition, we have documented temporal changes in students skills over the course of a semester, year, and from high school to college.

Two GIS modules were taught and completed by students at the high school and college levels. The first, Exploring the Dynamic Earth (Hall-Wallace, Walker, Kendall, Schaller & Butler, 2003a), consists of five units covering the topics of plate tectonics and geologic hazards. In the first unit, *Searching for Evidence*, students explore the relationship between topography and the plate boundaries using maps in orthographic and geographic projections, shaded relief maps, three-dimensional block diagrams and two-dimensional cross sections (figure 1). In the second unit, *Exploring Plate Tectonics*, students explore patterns in plate tectonics including two- and three-dimensional representations of the magnetic polarity changes in the sea floor. The third unit, *Earthquake Hazards,* students evaluate the distribution and characteristics of earthquakes, including images of their three-dimensional distribution at subduction zones and spreading ridges. In *Volcano Hazards*, the module's fourth unit, students explore the global distribution and eruptive hazards of volcanoes, including the aerial extent of ash deposition (figure 2). In the fifth unit, *Tsunami Hazards,* students view animations of the propagation of a three-dimensional tsunami wave as it crosses the Pacific Ocean.

The second GIS module, Exploring Tropical Cyclones (Hall-Wallace, Walker, Kendall, Schaller & Butler, 2003b), is a four-unit exploration of tropical cyclones. In the first unit, *Recipe for a Cyclone*, students view animations of satellite images of hurricane movement (figure 3) and explore the spatial distribution of cyclone formation. In the second unit, *The Life of a Cyclone*, students explore the relationship between variables that impact cyclones, including global wind patterns and hurricane tracks, sea surface temperature and average wind speed and the temporal distribution of major cyclones. In the third unit, *Hurricane Hazards*, students characterize the types of hazards present in different regions and evaluate the spatial distribution of damage. In *Hurricanes in the Big Apple*, the module's fourth unit, along with the shape and orientation of the coastline, students integrate regional topography, population, and infrastructure to evaluate cyclone risk. These directed activities enable students to analyze integrated tabular and geographic data, creating opportunities for students to develop their critical and spatial thinking skills.

We measured spatial skills of earth science students in five local high schools with which (author) has had long-term partnerships with the teachers. In two schools, students completed only a few GIS units; therefore their data were not included in study. In the third school (HSE), students completed seven units, *Recipe for a Cyclone*, *The Life of a Cyclone*, *Searching for Evidence*, *Exploring Plate Tectonics*, *Earthquake Hazards*, *Volcano Hazards*, and *Tsunami Hazards* which required over 20 hours of instruction in the computer laboratory in addition to time spent finishing the questions as homework. HSE is an urban school with approximately 1,500 students. Primarily freshman and sophomores enroll in the year-long earth science course. Two other high schools (HSC) served as a control group. The first was a rural high school with 725 students, the second an urban school with approximately 1,400 students. Both offer a year-long earth science course for freshmen.

We also measured spatial skills in two large-enrollment introductory courses for non-science majors at the University of Arizona. Oceanography (Geos 212) is an introductory course focusing on the geological, physical, chemical and biological processes of the oceans; Geologic Disasters and Society (Geos 218) is an introductory course focusing on the scientific principles governing geological catastrophes and their affect on society.

Both courses meet the general education requirement in science, and enroll approximately 200 non-science majors each. Neither course included a laboratory section but both included lectures with a significant number of maps, animations and other types of visualizations of Earth processes. Students in Geos 218 were assigned the GIS modules as homework with the purpose of building their inquiry and scientific process skills, as well as reinforcing concepts presented in lecture. Students completed four GIS units, *Recipe for a Cyclone*, *Searching for Evidence*, *Volcano Hazards* and *Tsunami Hazards*. Each unit took the college-level students approximately two to three hours to complete. The control class, Geos 212 did not complete any homework or other exercises that included activities designed to develop spatial skills.

In addition, we measured the spatial skills of 44 geoscience majors in two introductory geoscience courses. These included students in Introduction to Physical Geology (Geos 251) and Computer Applications in Geosciences (Geos 256). Geos 251 is an introduction to Earth's materials, surface and internal geologic processes, plate tectonics and geologic time. The course meets three hours per week for lecture and three hours per week for a lab that includes practical experience with topographic and geologic maps and cross sections. This course also includes five field trips allowing students to explore geologic relationships in the field. Geos 256 emphasizes computer skills specific to the geosciences including familiarizing students with spreadsheets, graphics applications, mathematical tools and geologic databases. This course meets for two hours of lecture and three hours of lab each week for 15 weeks. These courses are the first courses taken as part of a degree in geosciences, thus the data set represents the spatial skills of typical first-year geoscience majors.

Design and Materials

We measured the change in spatial relations and spatial orientation skills of each student using tests from the Kit of Factor Referenced Cognitive Tests (Ekstrom, et. al, 1976). These tests were developed in the 1960's, and have long been used for analysis of spatial ability with predictive validity. Spatial relations ability was measured with the Cube Comparison test, which requires the subject to mentally rotate an object about its center. The subject is presented with a pair of cubes (figure 4), marked with a single letter, number, or symbol on each face. Each face is unique, with no letter or number repeated on a cube. The subject must choose whether the two cubes are the same or different. Analysis of the cubes involves mentally rotating one cube to assess if the cubes match on the visible sides. This test is timed, and subjects are given 3 minutes to complete 21 problems. Spatial orientation ability was measured with the Surface Development test. The subject is presented with a two-dimensional unfolded figure and a three-dimensional representation of the folded figure (figure 5). The subject must identify corresponding edges in the two different drawings. This requires the ability to imagine multiple movements of the unfolded figure. The two-dimensional figure must be mentally folded to align the edges. Subjects are allotted six minutes to evaluate six problems. On both the Cube Comparison and Spatial Orientation tests, students are penalized for guessing; their score is the number answered correctly minus the number answered incorrectly.

Procedure

All students completed pre- and post-tests of spatial ability to measure the change in their skills over a set time period. All college-level students took the pre-test early in the semester before the first homework was assigned; they took the post-test near the end of the semester after all of the activities were completed. The high school students completed the pre-test early in the fall during a two-week window approximately 1 month into the school year; they completed the post-test in the last few weeks of the school year. No feedback was given to the students or teachers on test results. High school students were required by their teacher to complete the test. Extra credit was given for returning a slip that gave permission for the authors to use the data in this research. At the college level, extra credit was given for completing the tests, regardless of the scores.

Students in the large-enrollment university courses were tested on a digital version of the paper tests administered by a computer-based testing program. Pellegrino, Hunt, Abate and Farr, (1987) showed that computer-based measures of spatial ability produced reliable results, comparable to pencil and paper tests. The tests for college geoscience majors were administered on paper, as were the tests for high school students.

Results

To measure changes in student spatial ability, we used pre- and post-test scores and paired T-tests to determine whether improvement in spatial ability was statistically significant. Improvement was considered significant for p value < 0.05. To compare the independent groups, we used one-way analysis of variance (ANOVA) of the mean scores. In addition, we calculated the Hake score for each group, which is a comparison of the improvement by a group, normalized by the maximum possible improvement. The Hake score provides a better metric of the growth in ability over the semester or school year than a simple percent increase because it takes into account the overall performance as compared to the maximum performance.

Table 1 summarizes average scores and standard deviations on pre- and post-tests of spatial relations for all students discussed in this study. Table 2 summarizes the data for the spatial orientation pre- and post-tests. For all groups, the study sample includes only students who completed the spatial ability tests both at the beginning and end of the course.

High School

All high school students began the study with statistically the same performance on the pre-test of spatial relations. Comparing post-test scores, we found that the improvement in spatial relations is statistically significant but the same for the high school control and experimental groups. Therefore, simple participation in a geoscience course results in an improvement in spatial relations ability. The GIS instruction appears to have had no measurable effect on student performance.

On the pre-tests of spatial orientation the average performance of the two groups was statistically similar. However, both groups have a very large standard deviation indicating a wide range of ability. The post-test scores show that the experimental group had a statistically significant improvement, while the control group showed almost no change at all. This difference in improvement could be attributed to the extended use of the GIS curriculum. Note that the standard deviations for both groups are more pronounced in the post-test scores, suggesting that some students have significant spatial orientation skills while others are deficient.

College Non-Science Majors

Geos 212 and Geos 218 are college-level geoscience courses for non-science majors. All students began these courses with statistically similar scores on the pre-test of spatial relations. As with the high school students, both classes showed a statistically significant improvement in average test scores, however, the improvement is the same, and the post-test scores are not statistically significantly different. This again is showing an improvement in spatial relations ability due to simple participation in a geoscience course.

On the test of spatial orientation there was no statistically significant difference between either the classes' performance on the pre-test or the post-test. There was no statistically significant improvement for either group. Further, in our exploration of the relationship between use of a GIS and spatial ability development, we were unable to measure an effect of the GIS curriculum on students' spatial relations or spatial orientation ability among students in introductory college courses.

In this data set, we had additional information about the students, including the final course percentage. The correlation between the final course grade percentage and the post-spatial relations test was 0.25 ($p < 0.03$) indicating that a relationship exists between this spatial measure and performance in the course. However, there is no correlation between the final course grade percentage and the post-spatial orientation test (0.04, $p < 0.70$).

College Science Majors

Data were collected from two courses (Geos 251, Geos 256) to evaluate college science majors. Both groups performed statistically the same on the pre-test of spatial relations and the pre-test of spatial orientation. Students showed statistically significant improvements over the course of the semester on both tests of spatial ability.

The improvements by majors on the test of spatial relations, evaluated by the normalized Hake score, are nearly triple the improvements of the non-science majors. Similarly, improvements are seen in the spatial orientation scores for Geos 251 and 256 that were not seen in the introductory geoscience courses for non-science majors. This suggests that simple participation in a geoscience course with more advanced content and a complex laboratory investigation results in improvement in both measures of spatial ability.

Analysis of Gender Differences

We have separated scores of each test group by gender in tables 3 and 4. For both the high school students and introductory non-science majors, our data does not reveal a difference between the sexes either in the initial or the final test scores. In both of these groups, the high standard deviations indicate that the students are exposed to different factors that are having more impact on developing spatial skills than the sex of the student. However, there are observable differences by gender among science majors. Males are starting the courses with a significantly higher ability on both tests; however, female students experience nearly double the improvement of males and have statistically indistinguishable skills from those of males at the end of the semester.

Group Comparisons

Comparing temporal changes in students' skills from high school to college required further analysis. The small sample size in the individual majors courses makes it difficult to draw conclusions about differences in abilities in the science student populations. We compared the scores of students in the two majors courses to determine if they were statistically different and found they are not. Therefore, we combined these data to characterize spatial abilities of geoscience majors. We did a similar comparison of Geos 212 and 218. Both the pre- and post-test scores for these two individual groups were statistically the same, thus the data were combined to characterize the average spatial abilities of non-science majors. Included for comparison are pre- and post-test scores for the high school control group, which most typically represents a high school population that will enter the University. The high school experimental group (HSE) was not included, due to the impact of the GIS on their post-test scores.

To compare temporal changes in students' skills, table 5 shows the pre- and post-test scores of spatial relations. The high school students are completing their freshman year with the average spatial relations ability of students entering the University, the averages for the high school post-test and the college non-science major pre-test are not statistically different. This raises questions about what spatial ability growth occurs for the remaining three years of high school. While there was no statistically significant difference on the pre-test performance between non-majors and majors, the post-test shows a differential growth in ability with the science majors having nearly triple the improvement in spatial relations ability when normalized.

Table 6 summarizes the pre- and post-test scores on the test of spatial orientation for all groups. Again, high school students are completing their freshman year studies with the average ability of students entering the University as non-science majors. On this test, there are significant standard deviations, revealing a wide range of abilities in all groups. However, there is a marked difference in the spatial orientation ability of incoming students depending on whether they are a science major or non-science major, with majors having significantly higher abilities.

Discussion

We were unable to measure an improvement in spatial relations ability that could be linked to the use of the GIS modules. All subjects improved their spatial relations ability, indicating that this skill can be improved by simple participation in a geoscience course. Growth in spatial orientation ability occurred both when the students used the GIS curriculum for an extensive period of time (HSE group) and in the courses that had a hands-on weekly laboratory experience (Geos 251, Geos 256). Developing this spatial ability likely requires more interactive learning and manipulation of objects or images than is offered in a typical lecture style learning environment.

Drawing conclusions from human subjects data is complex, correlations can be influenced by other factors related to the course instruction or curriculum materials. In addition, it is important to note that there is a significant standard deviation in all groups. In the introductory courses for non-science majors there are students with very high spatial skills. These are perhaps the students most likely to be recruited as science majors. However, there are also science majors with very low spatial abilities. Due to the prevalence of concepts that require spatial abilities throughout the degree program, identifying early those students that may require additional spatial training could improve retention of science majors.

While there is evidence of self-selection for science majors based on spatial ability, this may be an effect of previous coursework in the sciences. Blade and Watson (1955) have shown that while high scores indicate an aptitude, low scores do not necessarily indicate a lack of aptitude. With proper training and experiences, the potential exists for all students to develop the necessary spatial skills to evaluate science concepts. Integrating coursework that improves spatial abilities at the high school level will have a positive effect on students performance in science and may result in a larger number of students choosing science majors. Finally, the low average performance of students in the high school and introductory college courses suggests that we also evaluate teaching strategies in all courses to ensure that students can interpret and understand the visual imagery used in lectures.

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Table 1

Means and Standard Deviations for Pre- and Post-tests of Spatial Relations

	Mean (Pre)	SD	N	Mean (Post)	SD	Change	Hake
HSC	3.8	4.8	139	5.9	5.1	2.1 ($p < 0.0001$)	.12
HSE	4.3	5.3	94	6.8	5.6	2.5 ($p < 0.0001$)	.15
Geos 212	6.6	4.1	96	8.1	5.3	1.4 ($p < 0.01$)	.10
Geos 218	7.1	4.3	78	8.4	4.8	1.3 ($p < 0.02$)	.09
Geos 251	9.3	4.2	19	12.6	4.6	3.3 ($p < 0.004$)	.28
Geos 256	6.7	6.0	25	10.6	6.7	4.0 ($p < 0.005$)	.27

Table 2

Means and Standard Deviations for Pre- and Post- Test of Spatial Orientation

	Mean (Pre)	SD	N	Mean (Post)	SD	Change	Hake
HSC	2.2	10.8	113	2.3	13.2	0.1 ($p < 0.9$)	.00
HSE	5.0	11.5	92	8.9	12.3	3.9 ($p < 0.0001$)	.16
Geos 212	1.0	13.2	91	2.2	15.8	1.3 ($p < 0.14$)	.04
Geos 218	2.4	11.2	73	4.2	11.7	1.8 ($p < 0.08$)	.07
Geos 251	13.9	12.1	19	18.1	11.8	4.1 ($p < 0.003$)	.26
Geos 256	13.7	10.9	19	18.5	7.6	4.5 ($p < 0.06$)	.29

Table 3

Means and Standard Deviations for Tests of Spatial Relations

	Mean (Pre)	SD	N	Mean (Post)	SD	Change	Hake
High school Male	4.2	4.7	64	6.0	4.9	1.8 ($p < 0.003$)	.11
High school Female	3.4	4.9	75	5.7	5.3	2.3 ($p < 0.001$)	.13
Non-science major Male	7.5	4.4	74	8.6	5.4	1.2 ($p < 0.05$)	.08
Non-science major Female	6.4	4.0	100	7.9	4.8	1.5 ($p < 0.003$)	.10
Science major Male	8.5	6.2	24	11.9	6.2	3.3 ($p < 0.01$)	.27
Science major Female	7.0	4.2	20	11.1	5.7	4.1 ($p < 0.002$)	.29

Table 4

Means and Standard Deviations for Tests of Spatial Orientation

	Mean (Pre)	SD	N	Mean (Post)	SD	Change	Hake
High school Male	3.7	12.3	50	1.9	14.9	-1.8 ($p < 0.27$)	-.07
High school Female	1.0	9.5	63	2.6	11.8	1.6 ($p < 0.13$)	.06
Non-science major Male	2.3	12.7	71	4.2	15.9	1.8 ($p < 0.06$)	.10
Non-science major Female	1.0	12.1	93	2.3	12.6	1.5 ($p < 0.11$)	.07
Science major Male	17.9	10.5	20	20.3	9.3	2.4 ($p < 0.18$)	.20
Science major Female	9.3	11.0	18	16.1	10.2	6.7 ($p < 0.002$)	.33

Table 5

Means and Standard Deviations for Tests of Spatial Relations

	Mean (Pre)	SD	N	Mean (Post)	SD	Change	Hake
High School (HSC)	3.8	4.8	139	5.9	5.1	2.1 ($p < 0.0001$)	.12
Non Science Majors (212, 218)	6.8	4.2	174	8.2	5.1	1.4 ($p < 0.0001$)	.10
Science Majors (251, 256)	7.8	5.4	44	11.5	5.9	3.7 ($p < 0.0001$)	.28

Table 6

Means and Standard Deviations for Tests of Spatial Orientation

	Mean (Pre)	SD	N	Mean (Post)	SD	Change	Hake
High School (HSC)	2.2	10.8	113	2.3	13.2	0.1 ($p < 0.9$)	.00
Non Science Majors (212, 218)	1.6	12.3	164	3.1	14.1	1.5 ($p < 0.02$)	.05
Science Majors (251, 256)	13.8	11.4	38	18.3	9.8	4.4 ($p < 0.002$)	.27

Figure 1. Students examine plate boundaries from both a two- and three-dimensional perspective allowing an evaluation of the spatial distribution of earthquakes and volcanoes.

Figure 2. Students explore the spatial distribution of ash from a volcanic eruption.

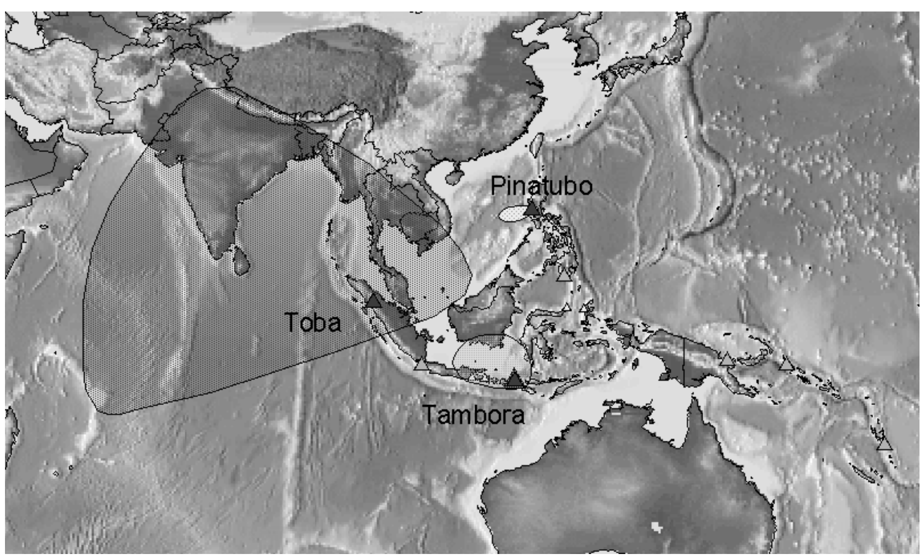

Figure 3. Students track the temporal changes in a hurricane from its formation off the coast of Africa to its arrival in the United States.

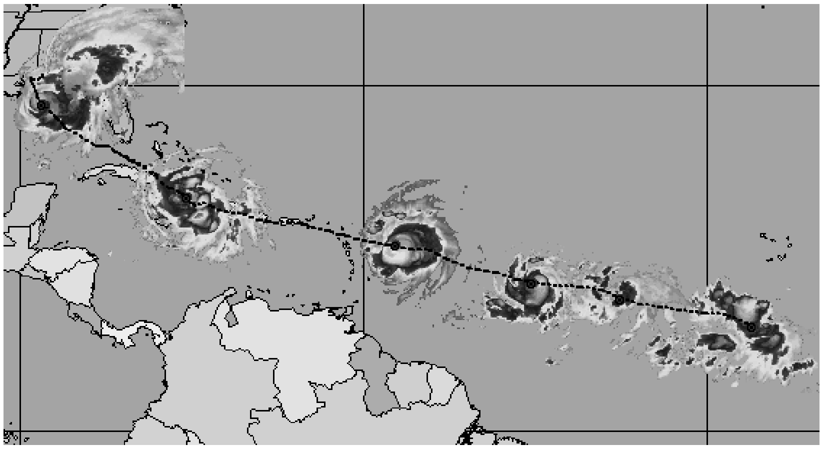

Figure 4. Sample item from the Cube Comparison test.

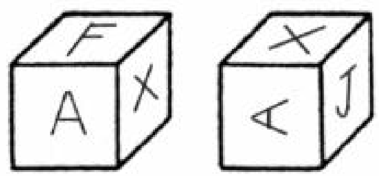

Figure 5. Sample item from the Surface Development test.