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RESEARCH REPORT

The role of visualization in learning from computer-based images

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Among the sciences, the practice of geology is especially visual. To assess the role of spatial ability in learning geology, we designed an experiment using: (1) web-based versions of spatial visualization tests, (2) a geospatial test, and (3) multimedia instructional modules built around QuickTime Virtual Reality movies. Students in control and experimental sections were administered measures of spatial orientation and visualization, as well as a content-based geospatial examination. All subjects improved significantly in their scores on spatial visualization and the geospatial examination. There was no change in their scores on spatial orientation. A three-way analysis of variance, with the geospatial examination as the dependent variable, revealed significant main effects favoring the experimental group and a significant interaction between treatment and gender. These results demonstrate that spatial ability can be improved through instruction, that learning of geological content will improve as a result, and that differences in performance between the genders can be eliminated.

Background

Visual–spatial ability

The exceptional role of spatial visualization in the work of scientists and mathematicians is well known. The German chemist August Kekule described how atoms appeared to 'dance before his eyes', and is said to have discovered the structure of the benzene ring by 'gazing into a fire and seeing in the flames a ring of atoms looking like a snake eating its own tail' (Rieber 1995: 48). Roger Shepard (1988) discusses many examples of how spatial visualization was important to the creative imagination of scientists like Einstein, Faraday, Tesla, Watson, and Feynmann.

The choice of a framework within which to study spatial abilities in the scientific realm is a difficult one. Spatial ability can be conceived of in a variety of ways, including recognizing rotated figures (Shepard and Metzler 1971), reasoning about the nature of space (Piaget and Inhelder 1967), disembedding and 'restructuring' information from visual arrays (Witkin et al. 1977), and 'mental imagery' (Shepard 1978). Each of these points of view represents an important and potentially productive starting point for research on the topic.

For the purpose of this study, we have chosen to identify spatial ability as a cluster of related but distinct qualities. Studies of traditional spatial measures show that they separate into at least two groups. Spatial orientation ('the ability to

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perceive spatial patterns or to maintain orientation with respect to objects in space') and visualization ('the ability to manipulate or transform the image of spatial patterns into other arrangements') are factorially distinct abilities (Ekstrom et al. 1976).

Spatial ability and success in science

The performance of scientists on standard tests of spatial ability is so high that Anne Roe (1961) had to create special measures for her studies of exceptionally creative scientists. Successful science students in high school and college have higher scores on traditional measures of spatial ability than is true of other students of their age and ability (Carter et al. 1987, Pallrand and Seeber 1984, Piburn 1980).

Many research reports have included significant positive correlations between spatial ability and success in classrooms. Topics studied have included biology (Provo et al. 2002), chemistry (Coleman and Gotch 1998, Tuckey and Selvaratnam 1993), engineering (His et al. 1997), and physics (Pallrand and Seeber 1984).

Despite the obvious importance of spatial visualization to the geological sciences, there are few studies that explore this relationship. Muehlberger and Boyer (1961) found that students' scores on a standard visualization test correlated positively with their grades in an undergraduate structural geology course, as well as with grades in previously taken geology courses. In a more recent study, Kali and Orion (1996) reported that the 'ability mentally to penetrate a structure', which they called visual penetration ability, is highly related to the ability to solve problems on their Geologic Spatial Ability Test.

Developing students' spatial ability

Although our schools specifically teach verbal and logical-mathematical skills, they rarely intervene in the spatial realm. This is surprising, since spatial ability can be taught, and the effects of such instruction have been shown to yield greater learning in science classes (Pallrand and Seeber 1984).

Practice with classification, pattern detection, ordering, rotation, and mental manipulation of three-dimensional objects can improve spatial ability. Zavotka (1987) used computer-animated graphics that 'replicate mental images of rotation and dimensional transformation' with university students. The intervention was successful in improving scores on orthographic tests, but not those of mental rotation. In a review of visualization research in chemistry education, Tuckey and Selvaratnam (1993) present a number of techniques that have been proven effective in improving spatial skills. These involve interventions in which students observe diagrams showing successive steps in the rotation of molecules, as well as computer-based programs showing rotating molecules and their shadows.

Lord (1985, 1987) succeeded in improving the spatial ability of college students by having them try to visualize sections through three-dimensional objects, and then cut the objects to verify their predictions. His rationale for these experiments was that asking a subject to 'picture in his mind the bisection of a three-dimensional form and to predict the two-dimensional shape of the cut surface' (Lord 1985: 397) conformed with the demands predicted by the Shepard–Chipman theory of second order isomorphism (Shepard and Chipman 1970). As individuals with poor spatial ability attempt to manipulate an image, they lose the one-to-one relationship between the mental image and the external object. Repeated practice appears to improve subjects' ability to maintain this correspondence between object and image.

Interventions constructed within the contexts of Piagetian theory have also been shown to improve spatial ability. Cohen (1983) conducted an experiment in which students in a control group were told to leave the experimental apparatus stationary, while those in the experimental group were encouraged to seek a variety of alternative perspectives from which to view the experiment. Post-test scores in the experimental group showed significant improvement over those in the control group on three of eight measures of Piaget's projective groupings.

Two studies (Eley 1993, Schofield and Kirby 1994) showed that topographic map interpretation was improved through intervention, but used drastically different procedures to achieve that result. Schofield and Kirby, using Paivio's (1990) dual-coding theory in the design of their experiment, found that location of a position on a map involved both spatial and verbal strategies, as would be predicted by the theory, and that training in a verbal strategy could lead to improved performance. In contrast, the study by Eley involved training students to visualize a landscape from a topographic map and to state how the map would look to different observers. The results indicated that the use of mental imagery was context specific, but that the choice of processing strategy was not — instead being more susceptible to the influence of training.

The issue of transfer is a very important one. Proposals to create programs that improve students' visualization skills will only take on educational meaning if it can be shown that there is transfer from learning of these skills to other, more general problems, and especially those containing significant content from the sciences. The treatment provided by Pallrand and Seeber (1984) is perhaps the most detailed that has been attempted in the science education field. Students in an introductory college physics course were 'asked to draw outside scenes' by viewing through a small square cut in a piece of cardboard. They were encouraged to draw the dominant lines of the scenery and to reduce the scene to its proper perspective. Subjects were also given a short course in geometry and a module from the Science Curriculum Improvement Study. With these materials, students learned to reorient their perceptual framework with respect to observers with different orientations (Pallrand and Seeber 1984: 510). Students who went through the training showed improved visual skills, and achieved higher course grades than those who were enrolled in the same course but were not part of the experiment.

Bridging the gender gap

Many authors trace our current awareness of the relationships among gender, spatial ability, and achievement to the work of Eleanor Maccoby and Carol Jacklin (1974). In their pioneering book, Maccoby and Jacklin outlined the impact of gender on intellect, achievement, and social behavior, and traced what was then known about the origins of psychological differences between the sexes.

In the category 'Sex Differences that are Fairly Well Established', the authors concluded that 'girls have greater verbal ability than boys' and 'boys excel in visual-spatial ability' (Maccoby and Jacklin 1974: 351). They also accepted the claim that boys are more analytic and excel in mathematical and scientific pursuits. Maccoby and Jacklin stated that 'boys' superiority in math tends to be accompanied by better mastery of scientific subject matter and greater interest in science' (1974: 89). This led them to wonder about the link among variables discussed here, and in particular 'whether male superiority in science is a derivative of greater math abilities or whether both are a function of a third factor' (Maccoby and Jacklin 1974: 89). It was not difficult for most people working in the field to reach the tentative conclusion that spatial ability might be the link between gender and achievement in mathematics and science.

The results of training studies on gender differences are mixed. Some (Ben-Chaim et al. 1988, Cohen 1983, McClurg 1992) have shown no significant differences in the effects of training on spatial ability between females and males. In others, if improvement has occurred it has been approximately equivalent for the two genders, whether or not initial differences in spatial ability were observed. A third group of studies (Devon et al. 1998, Lord 1987, Vasta et al. 1996) have shown that it is possible to use such interventions to improve the spatial ability of women differentially over that of men. These studies have typically involved cases where there were initial differences between males and females on pre-tests, but not on post-tests. We have reviewed no studies that have shown the spatial ability of males to improve more than that of females as the result of an intervention on spatial ability.

Rationale

From a rich trove of basic research in the cognitive sciences, as well as a more modest literature in science and geoscience education, it has been possible to isolate the processes of spatial orientation and visualization as crucial to the thought process of scientists. What we have constructed is a small demonstration project, carefully designed and executed, that substantiates the claim that this element of geological reasoning can be taught, and will transfer to improved performance in geology courses.

The specific objectives of the project are:

- to show that it is possible to train students to use spatial skills in real geological contexts;
- to demonstrate that such training improves performance on traditional measures of spatial ability;
- to eliminate gender differences in spatial ability in a selected group of subjects;
- to show transfer from such training to extended context problems in novel settings; and
- to create innovative new computer-based materials that can be made available through the world wide web to instructors at colleges and universities.

The study

This project was designed to create and evaluate a group of computer-based modules for college-level instruction in geology. These modules focus on problems involving the surface expression of structural features and the shallow structure of the Earth's interior.

Our intention was to embed spatial learning in the context of real-life, complex problems that are authentic. They were taken from among actual problems that geologists deal with in everyday life. Computer-based materials were built with the Corel Program, Bryce©, which allows the creation of detailed and realistic, two-dimensional representations depicting three-dimensional perspectives of simple and complex geologic structures and landscapes.

Our expectation was that this would foster spatial skills and improve the transfer to relevant problem-solving. This hypothesis was tested in a quasi-experimental design in which control and experimental groups were administered a content assessment and two spatial/visual measures as pre-tests and post-tests.

The context

The experiment was conducted in four sections of Geology 103, a one credit-hour introductory geology laboratory associated with a 3-hour lecture course, Geology 101, 'Introduction to Geology'. The laboratory course enrolled approximately 100 students divided among four sections.

Four sections of Geology 103 were taught, each by a different graduate teaching assistant. Two sections each were assigned to the control and experimental conditions. To eliminate time-of-day effects, a control and experimental group were assigned to each starting time. Teaching assistants were fully briefed on the nature of the experiment, and members of the research team met with them weekly to discuss the nature of the experimental and control conditions. Members of the research team also observed both control and experimental classes on a regular basis to ensure that the experimental conditions were being met.

Both control and experimental classes studied from a laboratory manual written by Reynolds et al. (2001). This manual covers the traditional content of an introductory geology laboratory in an unconventional manner. The first seven chapters are anchored in a series of computer simulations created in a virtual environment we call Painted Canyon. In these chapters, students are introduced to topographic maps, minerals and rocks, geologic maps and geologic history, and environmental issues. Chapters 8–11 are devoted to the geology of selected regions of Arizona. The final three chapters engage students in a series of applied investigations.

The experimental group experienced two additional computer-based modules. The content of these was topographic maps and interactive three-dimensional geological blocks. Both modules allowed extensive student involvement with images that could be manipulated. Visualizations of geologic features with topographic maps draped on them could be rotated, sliced, or flooded with water. The interactive geological blocks could be rotated, sliced, or made transparent. Students spent a total of approximately 4 hours studying the two modules.

Data for time to completion and total correct were collected for the spatial orientation and spatial visualization measures. The spatial orientation measure, a modification of the Cubes Rotation Test, had Cronbach alphas of 0.90 for time to completion, an indication of very high internal consistency and reliability, and of 0.53 for total correct. The spatial visualization measure, a modification of the Surface Development Test, had Cronbach alphas of 0.96 for time to completion and of 0.94 for total correct.

The dependent variable was a 30-item geospatial assessment based upon the content of the laboratory manual (Reynolds et al. 2001). It included questions about topographic maps, perspective taking, geologic cross-sections, and other visually oriented aspects of the course. The geospatial assessment was administered as a paper-and-pencil test to all students in all sections on the first and the last days of the first summer session. They were told that their grade in the course would depend in part on their performance on the second content assessment. The Cronbach alpha for this instrument was 0.75 for the pre-test and was 0.78 for the post-test, showing high reliability.

Results

The sample consisted of 103 subjects, of whom 48 were male and 55 were female. The groups were unequal in size, with 44 subjects in the control group and 59 in the experimental group. Although subjects self-selected into individual sections of the course, the distribution by gender across the sections was not random. Males exceeded females in the control group by a factor of 1.4/1, and females exceeded males in the experimental group by a factor of 1.7/1.

This unusual sample bias is a classic example of the difficulties of quasi-experimental design with intact groups. The normal assumption of a quasi-experimental design of the sort used in this study is that the comparison groups will be equivalent. This has not turned out to be the case in this instance. As will be shown in the analyses that follow, initial mean scores on many variables were lower for females than for males. This has led to a set of results in which initial mean scores of the experimental group tend to be significantly lower than those of the control group.

The geospatial test

The effects of the experiment are analyzed through the application of a three-way analysis of variance. In this analysis, the dependent variable is performance on the Geospatial Test. SCORE reflects differences in performance from pre-test to post-test, and is treated here as a repeated measure. CONDITION refers to control versus experimental group, and GENDER to males versus females. The results are presented in table 1.

There was a significant main effect for SCORE, with higher post-test than pre-test scores for the entire sample. There were significant two-way interactions between SCORE and CONDITION, and between SCORE and GENDER. There was no significant three-way interaction.

In order to assess the magnitude of the experimental effect, normalized gain scores were computed for each student. Often referred to in the physics education

Table 1. Three-way analysis of variance (SCORE x CONDITION x GENDER) of scores on the Geospatial Test.

	F	*Degrees of freedom*	p
SCORE	161.266	1, 85	0.00*
SCORE x CONDITION	3.844	1, 85	0.05*
SCORE x GENDER	4.853	1, 85	0.03*
SCORE x CONDITION x GENDER	0.213	1, 85	0.65

Note: * $p \leq 0.05$.

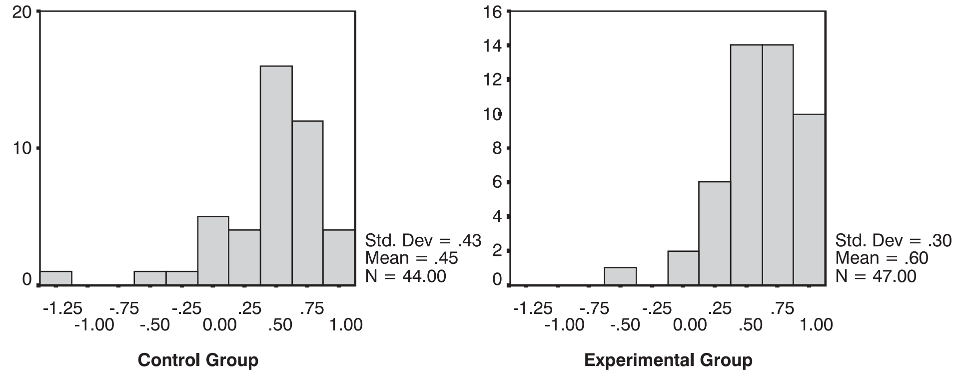

Figure 1. Normalized gain scores of experimental and control groups on the Geospatial Test.

literature as 'Hake Scores', these reflect the increase from pre-test to post-test score as a percentage of the total possible increase (normalized gain = post-test – pre-test/ total possible – pre-test). The results are displayed as histograms in figure 1.

The mean control group gain scores were 0.45 (45%), and the distribution remained normally distributed. In contrast, mean experimental group gain scores were 0.60 (60%) and badly skewed as a result of a ceiling effect. A large number of students in the experimental group achieved gains in the upper ranges, 75% and above. If the Geospatial Test had been somewhat more difficult, it is likely that the distribution of experimental group scores would also have been normal, and the differences between the means even greater.

Normalized gain scores for the entire sample are displayed separately by gender in figure 2. They are larger for females (56%) than for males (48%). While there is a slight ceiling effect for females, it is not as dramatic as the earlier example.

Figure 3 demonstrates the importance of gender as a variable in performance on the Geospatial Test. Females in both the control and the experimental groups experienced greater growth in their Geospatial Test scores from pre-test to post-test than

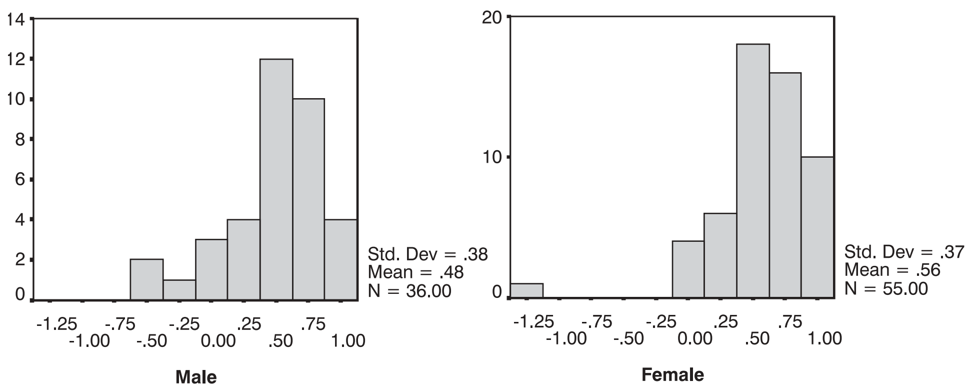

Figure 2. Normalized gain scores of males and females on the Geospatial Test.

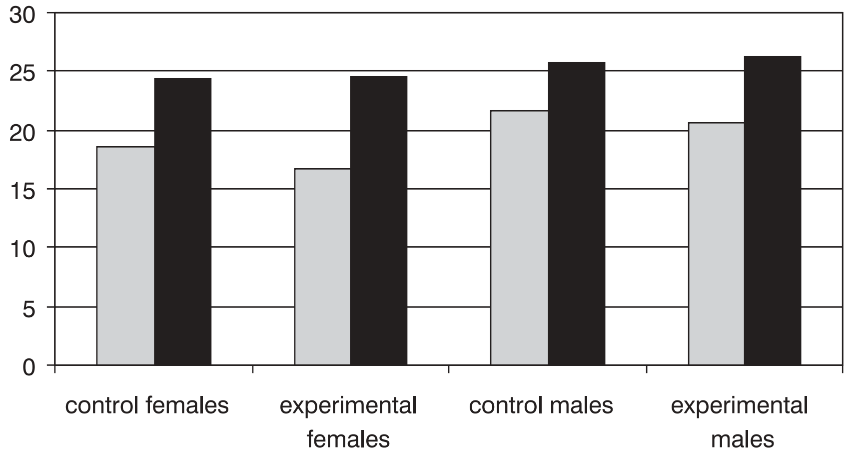

Figure 3. Pre-test (left) and post-test (right) means of males and females in experimental and control groups on the Geospatial Test.

did males. Although the effect was smaller, both males and females in the experimental group showed greater improvement than those in the control group. These results are exactly what were expected from the observation of a CONDITION x GENDER interaction.

The spatial measures

Two scores, the first for the total score and the second for the time to completion, were generated for each of the two spatial measures. A three-way analysis of variance revealed no significant main effect or interactions for the total score on the measure of spatial orientation. There was a significant main effect for time to completion ($F = 16.956$; degrees of freedom = 1, 82; $p = 0.00$), but there were no interactions with either CONDITION or GENDER. All subjects, both male and female in both the control and the experimental groups, showed improved time to completion on this measure.

The results for spatial visualization were somewhat different (table 2). In this analysis, SCORE refers to the test of spatial visualization administered as a repeated measure, CONDITION refers to control versus experimental groups, and

Table 2. Three-way analysis of variance (SCORE x CONDITION x GENDER) on total score on the spatial visualization measure.

	F	*Degrees of freedom*	p
SCORE	4.533	1, 82	0.04*
SCORE x CONDITION	6.830	1, 82	0.01*
SCORE x GENDER	1.096	1, 82	0.30
SCORE x CONDITION x GENDER	0.618	1, 82	0.43

Note: * $p \leq 0.05$.

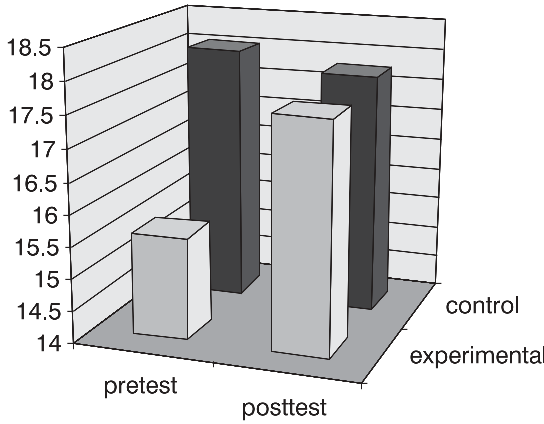

Figure 4. Pre-test and post-test mean total scores of experimental and control groups on the spatial visualization measure.

GENDER to males versus females. There was a significant main effect for SCORE, and a significant interaction between SCORE and CONDITION. There were no interactions between SCORE and GENDER, nor were there any three-way interactions.

As demonstrated in figure 4, the effect of the experiment was to equalize initial differences in spatial ability between the two groups. On the pre-test the experimental group visualization scores were much lower than those for the control group, whereas on the post-test the scores of the two groups were quite similar. Because there was no significant interaction between SCORE and GENDER, it appears that the effect was about the same for females as for males.

This was not the case for time to completion on the test of spatial visualization (table 3). In this instance, there was a significant main effect for time to completion, with students completing the post-test more quickly than the pre-test, and a significant interaction between SCORE and GENDER. There was no significant interaction between SCORE and CONDITION, nor was there a significant three-way interaction.

Figure 5 shows the effects of gender on time to completion. In this case, males began the experiment with somewhat longer times to completion than females, and the two groups were about the same at the end.

Table 3. Three-way analysis of variance (SCORE x CONDITION x GENDER) for time to completion on the spatial visualization measure.

	F	*Degrees of freedom*	p
SCORE	75.899	1, 82	0.00*
SCORE x CONDITION	2.199	1, 82	0.14
SCORE x GENDER	5.683	1, 82	0.02*
SCORE x CONDITION x GENDER	0.115	1, 82	0.74

Note: * $p \leq 0.05$.

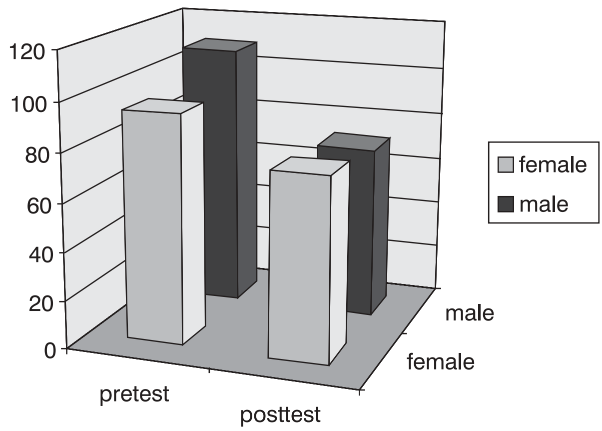

Figure 5. Pre-test and post-test mean times to completion of females and males on the spatial visualization measure.

Spatial ability and achievement

The only significant correlations between measures of spatial ability and the geospatial test were those measuring total score, so time to completion was eliminated as a variable in further analyses. However, the correlations between total scores on the spatial and geospatial measures are quite high, ranging from a low of 0.39 to a high of 0.57. This reflects shared variances (r^2) averaging 19% for spatial orientation and 29% for spatial visualization between the spatial and geospatial measures.

Because students entered the course with a good deal of prior geospatial knowledge, and because of the high correlations between spatial and geospatial ability, it was necessary to estimate the variance in post-test geospatial scores that was shared with spatial scores after the contribution of initial ability had been accounted for. In order to accomplish this, a stepwise multiple regression analysis, with pretest geospatial scores entered as a covariate at the first step, was completed (table 4). Prior knowledge, as measured by the Geospatial Test, and initial ability at spatial visualization yielded significant beta values in this analysis. The beta value for pretest scores on the spatial orientation measure did not reach statistical significance at the 0.05 level of alpha.

The variance shared between the post-test geospatial ability and all pre-test variables of spatial and geospatial ability was 38.4% ($r = 0.620$). The relative influence

Table 4. Regression of post-test geospatial scores against pre-test scores of spatial orientation and visualization and of geospatial ability.

	B	*Standard error*	*Beta*	t	p
(Constant)	16.009	1.992		8.306	0.000*
Pre-Geospatial	0.291	0.085	0.373	3.433	0.001*
Orientation	4.4×10^{-2}	0.162	0.032	0.275	0.784
Visualization	0.173	0.074	0.296	2.339	0.022*

Note: * $p \leq 0.05$.

of the separate factors in the equation can be evaluated by comparing beta weights, or standard partial regression coefficients, of the independent variables. Such a partial coefficient expresses the change in the dependent variable due to a change in one independent variable with the remaining variables held constant. In any regression, beta weights are the same regardless of the order in which the variables are entered.

Both prior knowledge and visualization ability contributed significantly to the equation predicting post-test Geospatial Test scores. Although the beta value for prior knowledge was somewhat higher than the beta value for spatial visualization, the two are similar enough to state that as a first order approximation the two contribute equally to the regression equation.

Summary

Although all subjects profited from both the control and the experimental conditions, the effectiveness of the treatment experienced by the experimental group has been confirmed. Using both analysis of variance and a comparison of normalized gain scores, it has been demonstrated that students in the experimental group profited more than those in the control group.

Very powerful gender effects have also been demonstrated. The experiment had the result of equalizing the performance of males and females in a case where the performance of males was initially superior to that of females. Again, although females profited from both treatments, it appears that the experimental condition was slightly preferable.

There was no significant effect on the abilities of students in spatial orientation as a result of either condition, nor did this variable affect achievement. This was not, however, the case for spatial visualization. The experimental treatment was very effective at improving scores and lowering times to completion. In this instance, the performance of males appears to have been differentially improved over that of females. A regression of performance on the post-test Geospatial Ability measure against pre-test variables showed that the normalized regression coefficients for prior knowledge and visualization ability were quite similar.

Discussion

This project demonstrates that spatial ability can be improved through instruction, leading to improved learning, and that differences in performance between the genders can be eliminated with such an intervention. This result was reached through the creation and application of a set of innovative, computer-based materials that can be widely used in introductory laboratory courses at colleges and universities. But more importantly, this study provides evidence from a naturalistic setting that demonstrates the effectiveness of those materials.

Spatial orientation and visualization are commonly understood as factorially distinct mental abilities (Ekstrom et al. 1976). In our study, participants improved in visualization, but not in spatial orientation. In addition, visualization is a significant predictor of the amount learned in the laboratory, but spatial orientation is not. Even more important is the finding that visualization and prior knowledge have approximately equal predictive power for post-test knowledge scores. This may be the strongest demonstration yet of the potency of spatial ability in facilitating learning, and of the importance of being able to visually transform an image to the nature of that learning process.

Because of time limitations and difficulties with preparing computer-based materials, we limited our inquiry to the most obvious and well-known examples of spatial ability. Even then, questions remain about the nature of spatial orientation and visualization, and how these interact with student learning. The observation of significant correlations is interesting, but we must now move forward to an explanation of how students manipulate images and use that information to generate knowledge. We expect that this answer will not be reached through quasi-experimental studies such as this one. In fact, we hope to soon begin a series of studies of a more qualitative nature in which the question of how students use images to negotiate meaning is addressed.

At least two other important spatial factors remain unexamined in our study. The first is the process of 'disembedding' or 'restructuring', as defined by measures such as the Embedded Figures Test. We are confident that this is an important variable, and available tests are adequate for an appropriate study. However, we have not yet completely defined how a working geologist would apply this ability to field studies, nor have we been able to create computer-based activities that mimic this process. We intend to create an interactive, computer-based module that involves disembedding figure from ground in realistic geological contexts, and replicating the current study in the near future.

Although we did not examine the variable of visual penetrative ability discussed by Kali and Orion (1996), we did observe student behaviors consistent with the influence of such a factor. This was especially true in problems involving block diagrams. When attempting to interpret a block penetrated by an inclined plane, many students seemed unable to see the projection of the plane through the block. When asked to complete a drawing of the intersection of a plane with the block faces, students often continued the line from the known face across the unknown one as though it were a linear rather than a planar element. The line seemed to be perceived as something that wrapped around the outside of the block in a continuous fashion. We also observed many solutions where the line was drawn at an angle intermediate between this interpretation and the correct one, as though students had an insight but were drawn perceptually to the incorrect solution. We also observed that this problem generated spirited discussions within groups where the correct and incorrect interpretations were held by members.

This study also has important implications to the issue of factors that influence the success of women in science. Gender differences in both spatial ability and achievement have been found by almost all those who have studied the topic. As suggested in our review of the literature, the question of the origin of these differences has not been answered. In this study, a relatively brief intervention succeeded in eliminating gender differences in spatial ability and closing the performance gap between males and females. This replicates a recent finding, in a study of success in engineering, in which it was found that females improved more than males in spatial ability (Hsi et al. 1997). Both results speak very strongly in favor of the position that observed gender differences are the result of differences in experience, and not of innate mental abilities, and that they can be eliminated by relatively minor treatments.

Much of the research comparing technology-based instruction with other methods has proven to be inconclusive. Among published studies and reviews, some show positive results for technology (Mann et al. 1999), while others show neutral (O'Sullivan and Weiss 1999) or negative results (Ravitz et al. 2002, Weglinsky 1998). Technology, like any other tool, can yield good results when used properly, or poor results when used inappropriately. It is our opinion that the superiority of computer-based education is most evident in cases where it is not possible to deliver the instruction by any other means.

We also present these modules as a proof-of-concept for the use of computer-based instructional materials in a constructivist context. We allow students to begin their work with a playful, exploratory investigation of a variety of images. They work in groups, interacting with the computer and using worksheets to record their emerging interpretations of what they are seeing. We ask them to create pictures in their mind long before we offer formalisms such as the definition of contour intervals or the names of particular kinds of folds or faults.

We believe that there is a structure of the discipline of geology that is especially important, perhaps more so than in other sciences. To construct theories about the Earth, geologists must visualize in time and space, from very short to inappreciably long times, and from atomic to continental scales. While the more traditional processes of science, such as controlling variables in experiments, remain important, they are less important than temporal–spatial reasoning in many subdisciplines of geology, especially those that involve reconstructing Earth history from field observations.

This study challenges conventional methods of teaching science. Rather than working from dull and uninteresting workbooks, students need to be engaged actively in realistic settings that are like those experienced by geologists themselves. Rather than dealing entirely in verbal forms of learning, they should engage all of the mental faculties, including but not limited to spatial visualization.

Finally, engaging in situated activities, such as the place-based approach used in the laboratory course, helps students to develop a set of intellectual skills that are demonstrably important to the learning of science and to the practice of geology. And it gives them some sense of what it is like to be a geologist. That, it seems to us, is among the most important goals of any course in laboratory science.

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