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The Spatial Thinking Workbook: A Research-Validated Spatial Skills Curriculum for Geology Majors

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ABSTRACT

Spatial visualization is an essential prerequisite for understanding geological features at all scales, such as the atomic structures of minerals, the geometry of a complex fault system, or the architecture of sedimentary deposits. Undergraduate geoscience majors bring a range of spatial skill levels to upper-level courses. Fortunately, spatial thinking improves with practice, and students benefit from intentional training. Several promising teaching strategies have emerged from recent cognitive science research into spatial thinking: gesturing, predictive sketching, and comparison, including analogy and alignment. Geoscience educators have traditionally incorporated many of these tools in their teaching, though not always consciously, intentionally, and in the most effective ways. Our research team, composed of geoscientists and cognitive psychologists, has collaborated to develop curricular materials for mineralogy, structural geology, and sedimentology and stratigraphy courses that incorporate these strategies intentionally and purposefully, supporting student understanding of the spatially challenging concepts and skills in these courses. Collectively, these two dozen learning activities comprise the Spatial Thinking Workbook (http://serc.carleton.edu/spatialworkbook/index.html). Pre- to posttest gains on a suite of assessment instruments, as well as embedded assessments, show that these curricular materials boost students' spatial thinking skills and strengthen their ability to solve geological problems with a spatial component. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-210.1]

Key words: spatial thinking, gesture, sketching, analogy, progressive alignment

PURPOSE AND LEARNING GOALS

Spatial Skills in the Geosciences

Spatial thinking is fundamentally important in the geosciences (e.g., Kastens and Ishikawa, 2006; Liben and Titus, 2012; Manduca and Kastens, 2012a, 2012b) yet is underinstructed in our educational system (NRC, 2006). As a result, students arrive in geoscience programs, including in upper-level courses for majors, with a range of skill levels on a variety of spatial thinking tasks (Ormand et al., 2014). Moreover, spatial thinking cannot be characterized as a single skill; it encompasses a suite of skills, including many essential to the geosciences: spatial visualization, mental rotation, penetrative thinking, navigation, and disembedding (recognizing patterns in incomplete or partially obscured visual stimuli) (e.g., Kastens and Ishikawa, 2006; Chatterjee, 2008; Riggs and Balliet, 2009; Liben and Titus, 2012; Manduca and Kastens, 2012b; Shipley et al., 2013; Ormand et al., 2014). Fortunately, spatial thinking skills are malleable (e.g., see the meta-analysis by Uttal et al., 2013). Indeed, one of the inspirations for the Spatial Thinking Workbook is the success of similar work in engineering. A course using an *Introduction to 3D Spatial Visualization* workbook increased student persistence and success rates in engineering (Sorby, 2009).

Considering the variety of spatial information that students are asked to process and the range of spatial problems students are asked to solve in three common undergraduate geology courses, we identified a set of spatial skills that are critical for success in those courses. We tailored the Spatial Thinking Workbook exercises to the development of those skills. We focus on upper-level undergraduate courses in geology, because we know that a significant number of students arrive in these classes with weak spatial skills (Ormand et al., 2014) and that lack of spatial skills can be a barrier to student persistence and success in science, technology, engineering, and mathematics (STEM) degree programs, particularly when students first encounter spatially challenging disciplinary concepts (Uttal and Cohen, 2012).

Learning Goals of the Spatial Thinking Workbook

While each activity in the Spatial Thinking Workbook has specific learning goals, the purpose of the workbook as a whole is to improve the spatial skills of students enrolled in undergraduate core geology courses, including mineralogy, sedimentology and stratigraphy, and structural geology. In particular, many of the workbook exercises focus on

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developing students' three-dimensional (3D) visualization and penetrative thinking skills: that is, their ability to visualize 3D objects and the objects' interiors. Themes of the learning goals for individual activities are that students will be able to visualize 3D spatial relationships from diagrams, use gestures to convey 3D spatial relationships, sketch a slice through a 3D object, and identify key similarities and differences between related 3D structures. For example, individual teaching activities specify learning goals as follows:

- "After successfully completing this exercise, students will be able to describe key differences between the structures of low-temperature and high-temperature forms of quartz" (Comparing Quartz Polymorphs exercise).
- "After successfully completing this exercise, students will be able to recognize channel deposits in outcrop and visualize the 3D shapes of channels that could produce the 2D cross-sectional shapes we see in outcrops" (Slicing Channels exercise).
- "After successfully completing this exercise, students will be able to use gesture to describe and illustrate axial planar, fanning, or transecting cleavage" (Folds and Cleavage exercise).

The full suite of activities can be found at http://serc.carleton.edu/spatialworkbook/activities.html.

LITERATURE CONTEXT

Strategies Emerging From Cognitive Science Research

Several promising teaching strategies have emerged from recent cognitive science research into spatial thinking. These include gesturing, predictive sketching, analogy, and alignment (e.g., Gentner and Markman, 1994; Goldin-Meadow, 2011; Gagnier et al., 2015; Newcombe et al., 2015). In our experience, traditional geoscience instruction often uses gesturing, sketching, and analogy, though not always in the ways that cognitive science research shows to be most effective.

Gesturing is familiar to most geoscientists as a means of communication, particularly for spatial information, but is less likely to be consciously employed as a teaching strategy. However, studies have shown that using gestures can facilitate student learning and that students who gesture learn spatial concepts more rapidly than those who passively watch their instructors gesture (but do not, themselves, use gestures) (e.g., Cook et al., 2008; Kastens et al., 2008; Goldin-Meadow, 2011). Similarly, students who were instructed to gesture and provide verbal explanations as they solved spatial thinking problems improved on a spatial problem-solving assessment, while students who were instructed to provide only verbal explanations did not (Atit et al., 2015). Cognitive scientists propose that this is because gesturing provides a mechanism for cognitive offloading: that is, it allows the "thinker" to do some of the mental work with his or her hands, thus freeing neural pathways in the brain to perform other cognitive functions (Goldin-Meadow et al., 2001).

Moreover, in studies of how geoscientists and students use gestures, cognitive scientists have made some surprising discoveries. In general, gestures that convey meaning are classified into one of two categories, either deictic (indicating an object in the conversational space by pointing or tracing) or iconic (indicating an object in the conversational space by depicting an aspect of that object). For example, pointing to a fold on a geological map is a deictic gesture, while holding one's hand in the shape of the fold is an iconic gesture. However, when asked to describe a cross-section on a geological map, structural geologists used deictic gestures, iconic gestures, and gestures that combine the characteristics of iconic and deictic gestures. These compound gestures, which are not captured by the existing classification, tend to occur when complex spatial information is not provided in speech (Atit et al., 2013). One implication of this result is that it may be helpful for instructors to inform students about what information is encoded in the instructor's gestures: location, shape, or both. Otherwise, students may be unaware that instructor gestures could be encoding both types of information simultaneously.

Furthermore, combining the right kinds of gestures with spatially descriptive speech may also be critical for learning spatial concepts. It may be self-evident that spatial information is difficult to convey using language alone. However, the use of gestures without spatial language may also be insufficient (Newcombe et al., 2015). For example, novice Earth Science students struggle when learning to interpret topographic maps. Atit et al. (2016) found that using pointing and tracing gestures to focus novices' attention on contour lines, accompanied by speech highlighting what information is encoded in the contour lines, can help the learner understand how to read topographic maps. The combination of gestures with language creates a meaning that is different and may be more coherent than what each modality conveys independently.

Students' gestures can also provide instructors with insights into the students' thinking. In a study of students' conceptions of sedimentary processes and stratigraphy, Herrera and Riggs (2013) found that students' correct use of representational gestures is an indicator of conceptual understanding. Intriguingly, mismatches between gesture and speech—where the gesture indicates a correct line of thinking—can also indicate that students are ready to learn a new concept (e.g., Broaders et al., 2007; Singer et al., 2008; Goldin-Meadow, 2011).

Sketching has long been a component of geoscience teaching and learning, particularly in fieldwork (e.g., Johnson and Reynolds, 2005; Marshak, 2015; Petcovic et al., 2016), and geoscience educators have used sketching both to develop and to assess student understanding of key concepts (e.g., Johnson and Reynolds, 2005; Sell et al., 2006; McNeal et al., 2008, 2014; Garnier et al., 2016). One value of sketching for these purposes is that sketches make a student's thinking visible to the instructor. Building on these ideas, cognitive science research on the use of sketching in geoscience learning has shown that predictive sketching, combined with immediate feedback on sketch accuracy, can be a powerful tool for learning (Gagnier et al., 2015, in press).

Predictive sketching is, as it sounds, the use of sketching to make a prediction. For example, a student can be asked to predict what a cross-section through a physical model of a geological structure will look like. Students who make a predictive cross-sectional sketch, immediately compare their

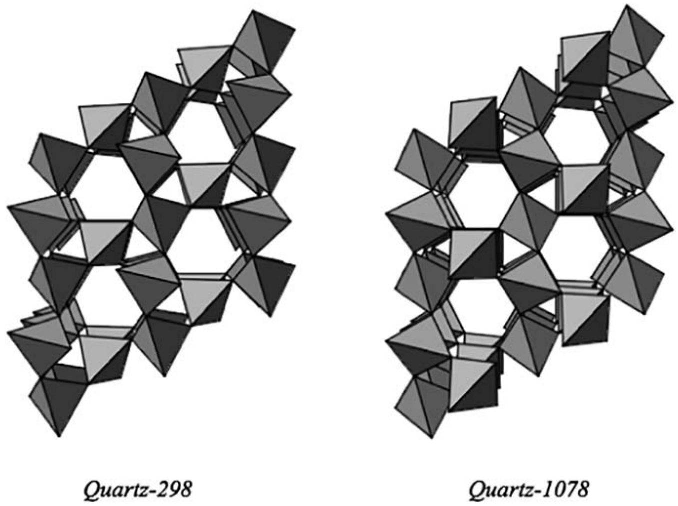

FIGURE 1: Visual comparison of the atomic structure of low-temperature quartz (left) to high-temperature quartz (right) shows that the low-temperature polymorph has threefold rotational symmetry while high-temperature quartz has sixfold symmetry. Cognitive scientists refer to the visual comparison of two objects that have a high degree of similarity, but also an important difference, as "alignment." These images were created using CrystalMaker software.

sketch to the correct answer, and then iteratively continue to make predictive sketches (e.g., of additional cross-sections), get significantly better at visualizing cross-sections of geological block diagrams (Gagnier et al., 2015, in press). What's more, they improve more than students who are asked to sketch the exterior of the block diagram or to visualize the interior structure without sketching it. Thus, neither sketching nor predicting alone is sufficient—it is the combination of these tasks that leads to spatial understanding (Gagnier et al., 2015, in press). While the idea of incorporating multiple sketching exercises into one's course can be daunting, this method does not require that an instructor grade the sketches. To the contrary, the need for immediate comparison to the correct answer suggests it is best implemented in class, with students evaluating their own sketches for accuracy.

As with gesturing and sketching, analogy is a common strategy used in teaching geoscience concepts (e.g., see Jee et al., 2010, and references therein; Davis and Fischer, 2016). An analogy is essentially a cognitive mapping of a target concept (something unfamiliar) onto a base concept (something familiar). Ideally, the cognitive mapping is a one-to-one mapping of similar components and relationships. Cognitive science research shows that analogies need to be carefully selected and presented and can easily introduce misconceptions (Jee et al., 2010; Resnick et al., 2016).

For example, one analogy for Earth's lithospheric plates is that they are like blocks of wood, floating on the asthenosphere just as wood floats in water. In this case, wood floating on water is the base concept, and lithospheric plates floating on the asthenosphere is the target concept. There is a one-to-one correspondence between lithospheric plates and blocks of wood and between the water and the asthenosphere. There are problems with this analogy, however. Students may learn (incorrectly) that the asthenosphere is fluid by mapping the properties of the base concept, water, onto the properties of the target concept. They may learn (again, incorrectly) that Earth's lithospheric plates are not usually in physical contact with one another, just as floating blocks of wood are not always touching one another—thus increasing the likelihood that students will conflate the concepts of plates and continents. In teaching with analogies, it is critically important to select analogies carefully and to call out, explicitly, key differences between the target concept and the base concept so that students do not unwittingly draw incorrect, but logical, conclusions about the target concept (Jee et al., 2010; Resnick et al., 2016).

The final instructional strategy we highlight is alignment. Alignment is simply a visual comparison of objects that share some similar characteristics in order to highlight important differences between them. For example, note that one can visually align a model of low-temperature quartz with a model of high-temperature quartz, and in so doing, one has threefold rotational symmetry (looking down the c-axis) while the other has sixfold symmetry (Fig. 1). In making such visual comparisons, students learn to "see" the alignable differences (e.g., Gentner and Markman, 1994).

The Purpose of This Project

Knowing that spatial skills are essential for success, underdeveloped in many undergraduate geoscience majors, and malleable, and being aware of the cognitive science research supporting the teaching strategies described above, we obtained funding from the National Science Foundation to develop curricular materials designed to improve students' spatial thinking skills. These materials focus on helping students understand challenging spatial concepts and master challenging spatial skills in three courses common in undergraduate geology curricula: Mineralogy, Structural Geology, and Sedimentology & Stratigraphy. We designed these curricular materials to help students in these courses develop both their domain-general spatial thinking skills (i.e., skills such as mental rotation) and their domain-specific spatial thinking skills (i.e., the ability to solve geological problems that require mental rotation, such as deducing the paleocurrent direction from cross-bed sets that have been rotated by folding or faulting). Our data show these materials to be effective at improving both domain-general and domain-specific spatial skills.

STUDY POPULATIONS AND SETTINGS

Our subjects were students enrolled in upper-level geoscience courses at three institutions over a 3-y period: Mineralogy and Structural Geology at two top-tier public research universities and Sedimentology & Stratigraphy at a private comprehensive university. The total number of participants in this study over the 3-y period was 181; the numbers of participants from each course, each year, are shown in Table I. Table II shows the gender distributions of the study participants in each course. We did not collect other demographic data.

Institutional review boards approved our study at all three institutions. Although all students in the courses took spatial thinking tests and completed homework, quizzes,

TABLE I: Numbers of study participants in each course, each year.

	Mineralogy	Structural Geology	Sedimentology & Stratigraphy	Annual Total
2011–2012	15	31	18	64
2012–2013	17	34	0	51
2013–2014	26	32	8	66
Total for the 3 y	58	97	26	181

and exams as part of the course requirements, the data reported here are only from students who chose to participate in the research study.

MATERIALS AND IMPLEMENTATION

Curricular Materials Development: The Spatial Thinking Workbook

The Spatial Thinking Workbook consists of teaching materials for mineralogy (eight activities), sedimentology and stratigraphy (five activities), and structural geology (seven activities), as well as five activities that could be used in any undergraduate geology course or in any of a variety of STEM courses incorporating spatial thinking. The geoscience faculty members on our team identified spatial concepts and tasks that are challenging for many of their students; we have chosen a few of these to describe in detail below. For each of these challenges, our interdisciplinary team of geoscience educators and cognitive scientists constructed one or more exercises, using the strategies and tools described above, to help students grasp the spatial concept or master the spatial task in question (Table III). All of these curricular materials are available on our project website: http://serc.carleton.edu/spatialworkbook/activities.html. Gesture exercises were implemented as in-class activities; the other exercises were implemented as in-class activities, as laboratory exercises, or as homework as the instructors deemed appropriate. Rather than describing all of the Spatial Thinking Workbook exercises here, we describe one example from each course, with each example selected to highlight the use of a different strategy. However, Table III summarizes the topics of and strategies used in the full suite of exercises.

Curricular Materials for Mineralogy

The exercises we developed for mineralogy focus primarily on understanding aspects of crystal structures, including crystal symmetry, Miller indices, bonding, and being able to visualize 3D structures from two-dimensional (2D) diagrams. In our experience, many undergraduate geology students struggle to visualize the atomic structures of minerals, and this compromises their ability to understand many of the key concepts in a typical mineralogy course. The strategies described above, supported by cognitive science research, provide a mechanism for students to move from 2D diagrams to 3D understanding.

For example, Miller indices are used in mineralogy to identify or describe the orientation of planes of interest, such as lattice planes, and their spatial relationship to crystallographic axes. We developed an exercise that uses gesturing to help students visualize and understand Miller indices. The Miller indices of a plane are the reciprocals of the a, b, and c intercepts of that plane. For instance, a plane that intersects the a-axis at ½, intersects the b-axis at 1, and is parallel to the c-axis is designated (2, 1, 0), because 2 is the reciprocal of ½, 1 is the reciprocal of 1, and 0 is the reciprocal of infinity. In our Spatial Thinking Workbook exercise, students use one hand to gesture the crystallographic axes and the other hand to represent a plane. The knuckles of the first hand can be used to designate intercepts so that a plane can be uniquely identified (Fig. 2). Pairs of students take turns gesturing planes to a partner, with the partner identifying the indicated plane. This practice helps students develop an understanding of how Miller indices are related to planes of a variety of spatial orientations.

Other mineralogy exercises within the Spatial Thinking Workbook target similarly challenging spatial concepts, using whichever cognitive support strategy our team thought best suited to developing student understanding of the concept.

Curricular Materials for Sedimentology & Stratigraphy

Our sedimentology and stratigraphy exercises focus on understanding primary structures, channel deposits, and 2D slices through 3D objects, such as fossils and conglomerates. For example, we use analogy to help students develop a deeper understanding of the properties of conglomerates. Identifying a conglomerate as clast- or matrix-supported is important for interpreting the depositional environment in which it formed. Many students, when examining a conglomerate, will assume it is matrix-supported if they cannot see points of physical contact between every pair of clasts. Yet clasts may be in physical contact with one another, within the interior of a rock, although we cannot see those points of contact.

We help students to understand this by using a bowl of rocks and sand as an analogy for a conglomerate. The analogy is a simple one: the sand in the bowl is analogous to

TABLE II: Gender distributions of the study participants in each course.

	Mineralogy	Structural Geology	Sedimentology & Stratigraphy	Total
Male	37	65	16	118
Female	13	24	10	47
Not Reported	8	8	0	16
Total for the 3 y	58	97	26	181

TABLE III: Topics and strategies of the exercises in the Spatial Thinking Workbook.

	Gesturing	Sketching	Analogy	Alignment
General Exercises				
Using Gestures to Support Spatial Thinking	x			
Slices Through 3D Objects		x		
Introduction to 3D Sketching		x		
Slicing Cylinders		x	x	
Slicing Fruit		x	x	
Exercises for Sedimentology & Stratigraphy				
Primary Structures and Rotation	x			
Sketching 3D Ripples and Dunes		x	x	
Slicing Channels	x	x	x	
Slicing Rocks	x	x	x	
Slicing Fossils	x	x		
Exercises for Mineralogy				
Gestures for Miller Indices	x			
Understanding Crystal Symmetry	x			
Deciphering Mineral Structure Diagrams				x
Understanding Polyhedral Diagrams				x
Comparing Quartz Polymorphs				x
Comparing Phyllosilicate Structures				x
Gestures for Silicate Structures	x			
Understanding Mineral Cleavage	x			x
Exercises for Structural Geology				
Linear and Planar Features	x			
Primary Structures and Rotation	x			
Sketching Block Diagrams		x		x
Contractional Strain	x			x
Folds and Cleavage	x	x		x
Restraining Bends and Releasing Bends	x			x
Deformation Mechanisms & Microstructures				x
Fault Separation	x			x

the matrix in a conglomerate, and the rocks are analogous to the clasts. Presented with a bowl of rocks and sand, most students will say it is analogous to a matrix-supported conglomerate. However, when the students subsequently watch sand poured into a bowl of rocks until the rocks are surrounded, they recognize that few clast–clast contact points are visible within a clast-supported conglomerate.

Curricular Materials for Structural Geology

Many of the exercises we developed for structural geology focus on visualizing 3D relationships or processes from 2D diagrams or information. In our experience, many undergraduate students in structural geology have a poor understanding of how to extrapolate three dimensions from 2D information and also make incorrect assumptions when they do so. Again, many strategies can be used to help students make sense of 3D structures.

For example, students often conflate fault separation with fault slip direction (Fig. 3). In our exercise on fault separation, we combine alignment with gestures to help students understand the relationship between fault separation and slip direction, the geometry of the faulted layers, and the perspective from which these are viewed. As described in the introduction of this paper, alignment is the visual comparison of things that have some shared characteristics in order to highlight their essential differences. In this case, students explore how it is possible for the same fault separation—the 2D geometry they might see in a map view—to result from different fault kinematics. This highlights the importance of observing more than the apparent offset in interpreting faulted terrains.

Curricular Materials for Any Course

One theme of the exercises in the Spatial Thinking Workbook is visualizing slices through 3D objects. Because this skill—penetrative thinking—is so fundamental to the geosciences (e.g., Kali and Orion, 1996; Titus and Horsman, 2009; Ormand et al., 2014), we include several exercises that

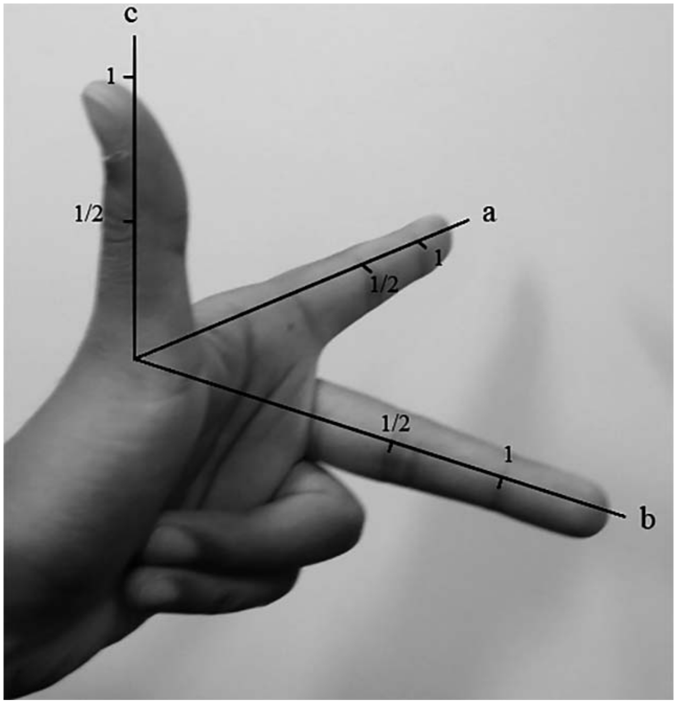

FIGURE 2: Gestures can be used to illustrate Miller indices. In this photograph, two fingers and the thumb of one hand represent crystallographic axes. Knuckles represent intercepts. Another hand (not shown) can be placed at various angles to represent planes of interest and explore their relationships to intercepts.

could be used in any course incorporating this skill. Predictive sketching is particularly well suited to the development of penetrative thinking, so we developed several exercises that use predictive sketching with familiar, nongeological objects. For example, in one exercise, students draw slices through fruit, beginning with single pieces of fruit and progressing to arrangements of multiple pieces. Each time the students complete a sketch, they are asked to compare their sketch to the correct answer. In this fashion, students who struggle—for example, with imagining a diagonal slice through an apple, pineapple, or banana—have the opportunity to assess their skill level and use the difference between their sketch and the correct answer to improve their mental models.

EVALUATION OF THE CURRICULAR MATERIALS

Research Design

We used a quasiexperimental research design to test the efficacy of the curricular materials we developed; it was an experimental design except that students were not randomly assigned to the control or experimental groups (Trochim, 2006). For our "control" group, we gathered baseline data from students enrolled in the Mineralogy, Structural Geology, and Sedimentology & Stratigraphy courses taught by the study faculty during the first year of our 3-y study. During this year, the faculty taught their courses as usual, using none of the curricular materials we were in the process of developing. For our "experimental" groups, we gathered comparative data from students enrolled in the same courses, at the same institutions, taught by the same faculty, the following 2 y. During these years, the faculty integrated the new curricular materials into their courses.

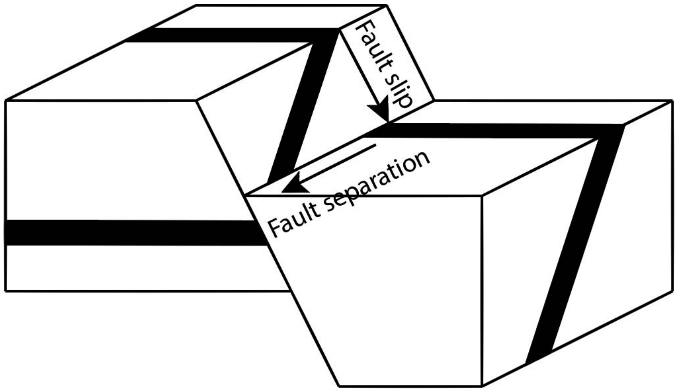

FIGURE 3: Fault slip is the vector showing motion along the fault surface. Fault separation is the apparent displacement. In this case, fault slip is normal, but after the footwall erodes to the same level as the hanging wall, the dipping layer will appear to have undergone strike–slip displacement. The fault separation for that layer, after such erosion, will be sinistral.

In each year of the study, we collected pre- and posttest measures of students' spatial thinking skills, as well as embedded assessments (e.g., questions on quizzes, exams, and homework exercises) of their skill in solving geological problems with a spatial component. The comparison of data from our control group to our experimental groups is beyond the scope of this paper and is instead the focus of another research paper (in preparation). In this paper, we present the data from the experimental groups—those students who completed the curricula described here. These data allow us to explore the relationship among workbook exercises, students' initial spatial thinking skills, and students' ability to solve spatial geological problems.

Data Sources and Data Collection

We administered a suite of spatial thinking pre- and posttests to study the range and development of students' spatial thinking skills. Pretests were administered during the first 2 weeks of classes, and posttests were given during the last 2 weeks of the semester. We selected the specific spatial thinking tests we included in this study to measure several aspects of spatial thinking that are important within mineralogy, structural geology, and sedimentology and stratigraphy. One of these is a mental rotation test (identifying which objects are the same in different orientations); three are tests of mental slicing, more formally known as penetrative thinking (choosing the correct image of a slice through an object); and one is a water level test (marking a horizontal line within a tilted frame of reference) (see Fig. 4 for example items from each test). These instruments, and our reasons for selecting them, are described in additional detail below.

While mental rotation, mental slicing, and the ability to recognize horizontal surfaces within a tilted reference frame are not the only important spatial skills in the geosciences, there are pervasive applications of these skills in the three

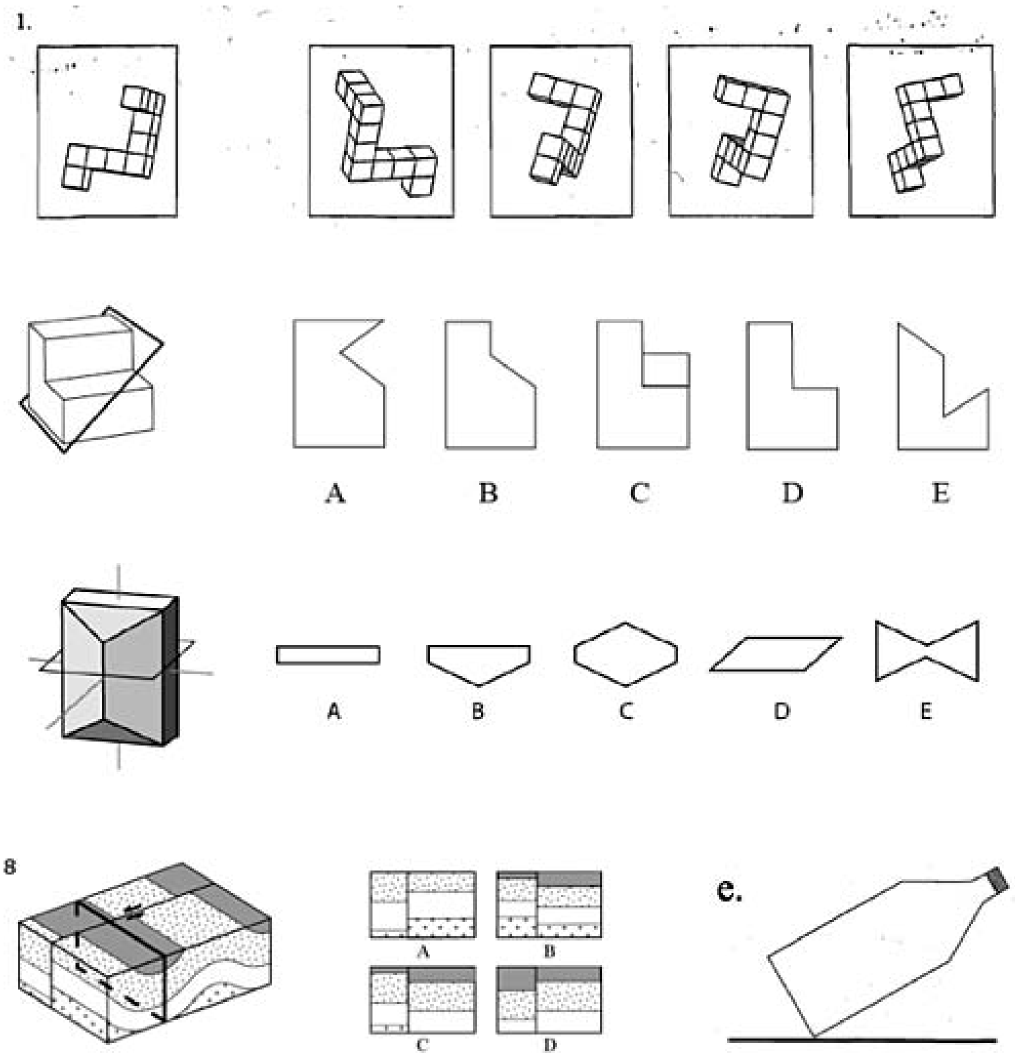

FIGURE 4: Example questions from each of the spatial skills tests we are using. (a) Mental Rotation Test A (MRT-A). Instructions: mark the two objects that are the same as the one on the left. (b)–(d) Mental slicing tests: (b) Planes of Reference Test, (c) Crystal Slicing Test, and (d) The Geologic Block Cross-Sectioning Test (GBCT). Instructions: choose the figure that shows what you would see on the slicing plane. (e) Water level test. Instructions: assuming that the bottle is half full of water, draw a line to show the top of the water surface.

courses included in this study. For example, mental rotation (visualizing the effect of rotating an object) is essential for understanding crystal symmetry, the use of stereonets, and visualizing the original orientation of tectonically tilted sedimentary strata. Penetrative thinking (visualizing spatial relations inside an object) is key to visualizing a slice through any object at any scale—a sheet silicate, a channel deposit, or a faulted ore deposit, for example. The water level test measures a student's ability to find a horizontal line or plane. This skill is essential for measuring strike and dip or for recognizing whether sedimentary strata have been tectonically tilted.

In each course, we also identified several embedded assessments that require applying spatial thinking to geological problems. In each of the three courses, we used the same embedded assessment questions all 3 y so that we could compare student performance on these items from one year to another, after controlling for differences in the student populations.

Spatial Thinking Assessment Instruments

We used the Vandenberg and Kuse Mental Rotation Test A (MRT-A) (Vandenberg and Kuse, 1978) as a test of mental rotation [Fig. 4(a)]. In this test, the subject is asked to choose the two answers that represent rotated copies of the stimulus; the other two possible answer choices represent rotated mirror images of that object. We chose the Vandenberg and Kuse test primarily because of its wide usage in cognitive science research (e.g., Peters et al., 1995) and because of its high degree of reliability, with a test–retest reliability of 0.83 (Vandenberg and Kuse, 1978).

To test penetrative thinking ability, we employed three instruments [Fig. 4(b)–4(d)]. The Planes of Reference Test, although not widely used to study spatial thinking, has been used in prior studies of spatial thinking in the geosciences (e.g., Titus and Horsman, 2009; Ormand et al., 2014) and has obvious surface validity as a measure of skill in visualizing the shape of a slice through a solid. We also developed two geoscience-specific tests of penetrative thinking: the Crystal Slicing

Test and the Geologic Block Cross-Sectioning Test. Both of these are multiple-choice tests of the subject's ability to recognize the correct cross-section through an idealized geological object, either a crystal form or a geological block diagram. The Crystal Slicing Test is quite similar to the Planes of Reference Test but uses shapes with which we expect students in mineralogy to be familiar. The Geologic Block Cross-Sectioning Test is inspired and informed by the work of Kali and Orion (1996), who explored high school students' abilities to visualize 3D structures via an open-ended block diagram test. The foils (wrong answers) in our Geologic Block Cross-Sectioning Test are based on the kinds of mistakes Kali and Orion (1996) observed and errors that we have seen on the open-ended prototype we used to develop our multiple-choice instrument. The Geologic Block Cross-Sectioning Test has also been used in prior studies of spatial thinking in the geosciences (e.g., Ormand et al., 2014; Hannula, 2015; Gold et al., 2016).

Our final spatial thinking assessment instrument was the Piaget water level test [Fig. 4(e)] (Piaget and Inhelder, 1967). In this test, the subject is shown a line drawing of a tilted bottle, resting on a flat surface. The instructions are to imagine that the bottle is approximately half full of water and to draw a line that shows where the top of the water's surface would be. Although most college students are able to do so successfully, a few students draw lines that are remarkably far from horizontal.

Embedded Assessments

In addition to the pre- and posttests of spatial thinking skills, we employed embedded assessments in each class. These took the form of homework, quiz, or exam questions that require applying spatial thinking to geological problems. Each of these questions focused directly on whether students had mastered a particular skill or concept from one of the Spatial Thinking Workbook exercises. For example, the Mineralogy course included an exam question about Miller indices, and the Structural Geology course included an exam question for which students have to interpret fault slip from data including fault separation.

Data Analysis

We compared students' pre- and posttest scores to measure the efficacy of our curricular materials in developing spatial thinking skills over the course of a semester. For each course, each corresponding set of study participants (the students in that course who took both pre- and posttest), and each test administered to that group, we have calculated the following:

- Average score and standard deviation, pre- and posttest
- Average improvement over the course of the semester
- The *p* values, using a paired, 2-tailed *t*-test of pre- and posttest scores
- Effect sizes, using Cohen's *d*
- Embedded assessment scores

We used SPSS Statistics to analyze the quantitative measures and scoring rubrics, developed by each instructor, to score the embedded assessments.

Validity and Reliability

As described above, we used five assessment instruments to measure students' spatial thinking skills. The MRT-A (Vandenberg and Kuse, 1978) and water level test (Piaget and Inhelder, 1967) are valid and reliable instruments, developed by cognitive scientists. While we do not know of any data on the validity of the other three instruments, all have a high level of surface validity; that is, each of the three purports to test the subject's ability to choose the correct slice through a 3D object, and each is composed of test items that are diagrams of 3D objects with a selection of possible 2D slices through them. Two of these tests—the Planes of Reference Test and the Geologic Block Cross-Sectioning Test—have been used in prior studies (e.g., Titus and Horsman, 2009; Ormand et al., 2014; Hannula, 2015; Gold et al., 2016). The reliability of all three tests has been established by having multiple geoscience experts complete the tests. Answers to items on the tests are undisputed.

Each of the embedded assessments used in this study was developed by the instructor for the course in which it was used as a homework, quiz, or exam question. These measures are therefore as valid and reliable as any such measure of student learning.

RESULTS

Effect of Curricular Materials on Students' Spatial Thinking Skills

Pre- and posttest scores show a distinct, statistically significant improvement in students' mental rotation and mental slicing (penetrative thinking) skills in most classes but no significant improvement on the water level test in any class (Table IV and Fig. 5). Using a paired, two-tailed *t*-test to calculate *p* values is appropriate; the pre- and posttest scores for each population we consider follow a normal distribution with homogeneous variance. We omit the Sedimentology & Stratigraphy classes from our statistical analyses due to small class sizes. However, we included the curricular materials for this course in this paper because the data from the Sedimentology & Stratigraphy classes mimic the trends of the data from the other courses.

Because *p* values are influenced by sample size, we also calculated the effect sizes using Cohen's *d,* a ratio of average improvement to variability in the sample. Whereas *p* values quantify the likelihood of a particular outcome, effect sizes measure the magnitude of the experimental effect. In general, a Cohen's *d* value of 0.20 is considered small, 0.50 is medium, and 0.80 is considered a large effect (Cohen, 1992). Thus, our calculated Cohen's *d* values indicate that (where gains are statistically significant) students are making moderate to large improvements on the skills measured by these tests (Table IV).

In addition, embedded assessment scores demonstrate that most students in these courses are able to solve geological problems with a significant spatial component after completing the exercises in the Spatial Thinking Workbook.

INTERPRETATIONS

Students arrive in upper-level geology courses with a range of skill levels on a variety of spatial thinking assessments. Pre- and posttest comparisons show that

TABLE IV: Average pre- and posttest scores on the spatial thinking instruments, for Mineralogy and Structural Geology, each of the years the Spatial Thinking Workbook exercises were used. Sedimentology & Stratigraphy data are omitted due to small class sizes (Table I).[1]

	2012–2013				2013–2014			
	Pretest	Posttest	*p*	Cohen's *d*	Pretest	Posttest	*p*	Cohen's *d*
Mineralogy								
MRT-A	7.8	10.1	0.01	0.6	8.8	12.2	<0.01	0.8
Planes of Reference Test	5.4	7.7	<0.01	0.7	5.2	7.0	<0.01	0.7
Crystal Slicing Test	6.7	9.9	<0.01	1.4	7.4	9.5	<0.01	0.8
GBCT	3.1	5.4	<0.01	0.8	4.2	5.5	0.01	0.5
Water level test	9.4	10.2	0.21 (NS)	—	9.1	9.2	0.92 (NS)	—
Structural Geology								
MRT-A	8.9	12.6	<0.01	0.9	10.9	15.3	<0.01	1.1
Planes of Reference Test	8.2	9.7	<0.01	0.7	7.7	9.6	<0.01	0.7
Crystal Slicing Test	10.4	11.4	<0.01	0.5	10.0	11.6	<0.01	0.6
GBCT	9.0	9.8	<0.01	0.3	8.9	10.1	<0.01	0.5
Water level test	11.3	11.2	0.56 (NS)	—	10.8	10.6	0.54 (NS)	—

[1] GBCT = Geologic Block Cross-Sectioning Test; NS = not significant.

students' spatial skill levels improve over the course of an academic term, suggesting that the Spatial Thinking Workbook exercises help students to think spatially (Table IV and Fig. 5). In general, there is an upward shift in the distribution of mental rotation and mental slicing test scores, although in some classes a few individual students earned lower scores on the posttest than on the pretest. Lack of improvement on the water level test could be due to several factors, including a lack of room for improvement (most students had near-perfect scores on the pretest), lack of improvement in the skill, or test fatigue (this was the last of the five tests given, so students may not have been giving it their best effort at the end of the term). Embedded assessment scores show that, for the most part, students who complete the Spatial Thinking Workbook exercises are able to solve spatial geological problems. This result is particularly encouraging taken in combination with the pre- to posttest improvements on spatial thinking assessments: together, these data suggest that the Spatial Thinking Workbook can help students to develop the kinds of spatial thinking skills they need to succeed as geoscientists.

LIMITATIONS

As with any classroom study, there are myriad possible confounding factors. For example, although the faculty members teaching the courses were the same throughout the study, no course had the same teaching assistants for all 3 y. In addition, weather events caused the cancellation of some classes and one field trip during the period of data collection. So, despite our best efforts to have the only differences in instruction from year to year be the implementation of the Spatial Thinking Workbook exercises, there were other differences, all beyond the instructors' control. Moreover, we cannot say with certainty that the completion of the Spatial Thinking Workbook exercises was the sole cause of the observed gains in students' spatial thinking skills. However, because the exercises in the workbook were developed based on laboratory-based cognitive science research that showed a direct effect of the strategies we employed on subjects' spatial thinking skills, we think it is reasonable to conclude that the improvements we observe can be attributed, at least partly, to these curricular materials.

IMPLICATIONS AND CONCLUSIONS

Our curricular materials led to significant gains in spatial thinking skills for students in the Mineralogy and Structural Geology courses. Furthermore, although our data set is too small to make the same claim for students in the Sedimentology & Stratigraphy course described here, we saw similar trends in the data from this course. Modest improvements over one semester suggest that larger improvements could be possible over multiple courses, as within a degree program. If the Spatial Thinking Workbook exercises, and others developed using the same principles and strategies, were woven through an undergraduate geoscience program, the gains in spatial thinking skills could be profound.

Interested faculty can use the process we used to develop additional spatial thinking exercises for the same or different courses. We encourage you to incorporate several of the Spatial Thinking Workbook exercises in your teaching first, to familiarize yourself with these strategies for teaching spatial thinking skills. When you are confident in your ability to use these strategies to teach spatial thinking, identify other spatial thinking tasks that present challenges to students. On what questions or tasks do students earn lower grades than you expect or hope? What questions do you or your teaching assistants hear most often? The next step is to analyze what it is about each task that is spatially challenging. Does it require visualizing a 3D object from 2D diagrams? Mentally rotating an object or set of objects? Visualizing a slice or slices through a 3D object? Some other skill or combination of skills? Finally, think about what strategy or strategies might help students with the task. If it's a task requiring mental visualization, would gesturing or an

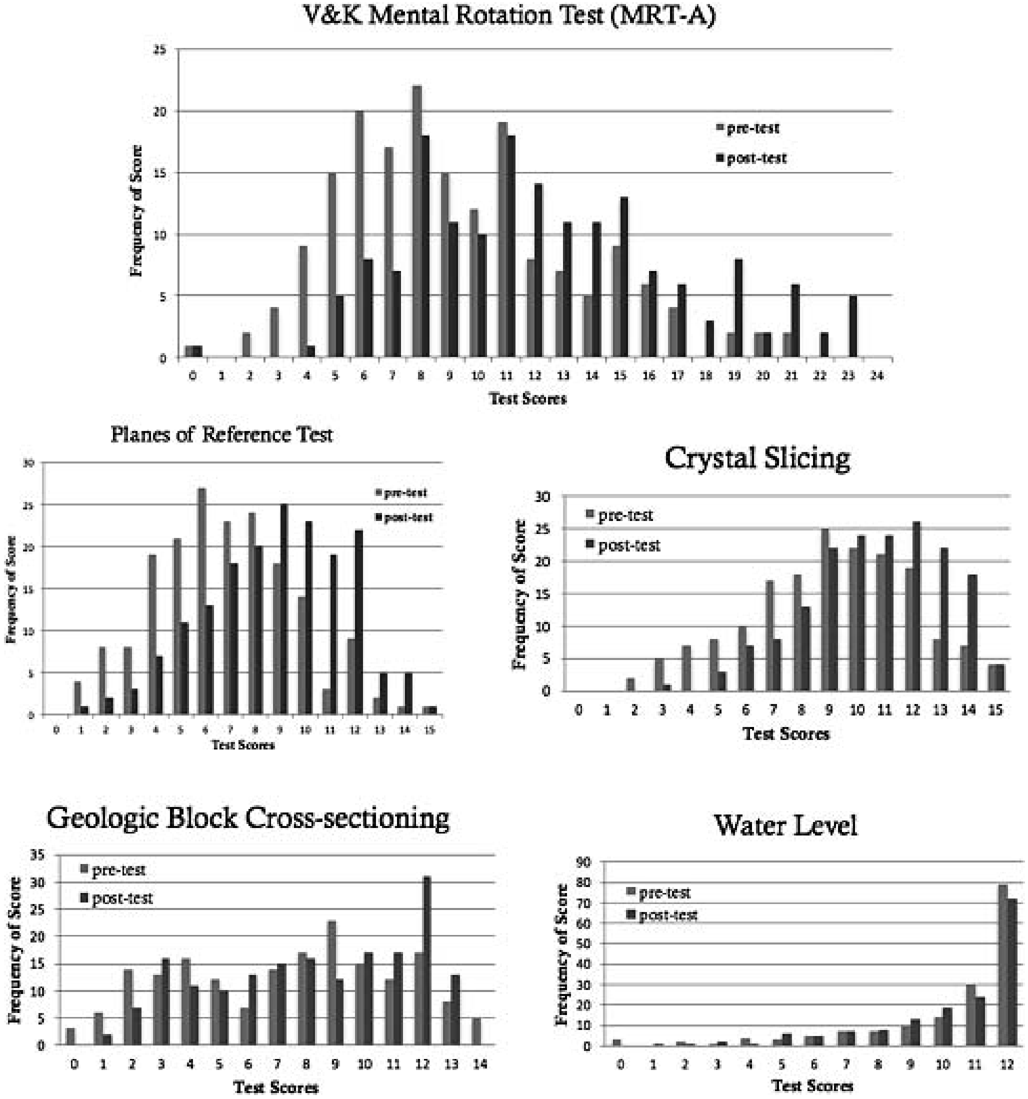

FIGURE 5: Graphs of the distributions of pre- and posttest scores, shown as a composite data set. Subsets of the data (e.g., for individual courses or years) show the same trends. We see statistically significant improvement on all but the water level test. See Table IV for average pre- and posttest scores by course and year. For each graph, the horizontal axis shows the range of possible scores on that test and the height of each bar shows the number of students with a particular score.

analogy help? If students have not yet learned terms of art for a complex spatial relationship, could they use gesturing to represent the key spatial relationships? If you want students to imagine something they cannot observe directly—a cross-section or how a feature will change over time—could they make a predictive sketch? If the goal is for students to recognize the key difference between two visually similar objects, alignment is a strong strategy. Focusing on the spatial skill you want students to develop facilitates the process of designing an effective activity to support that skill development.

Spatial thinking is essential in the geosciences, and intentional training of spatial thinking skills makes a difference. We have focused here on strategies that cognitive science research has demonstrated to be effective for strengthening spatial thinking skills: gesturing, predictive sketching, analogy, and alignment. We have illustrated how these strategies can be used to design effective curricular materials for upper-level geology courses. Adding these strategies to our teaching toolkits will facilitate the development of our students' spatial thinking skills.

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