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Analysis of Spatial Concepts, Spatial Skills and Spatial Representations in New York State Regents Earth Science Examinations

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ABSTRACT

Research has shown that spatial thinking is important in science in general, and in Earth Science in particular, and that performance on spatially demanding tasks can be fostered through instruction. Because spatial thinking is rarely taught explicitly in the U.S. education system, improving spatial thinking may be "low-hanging fruit" as far as improving science education. In this paper we have analyzed, categorized, and quantified the occurrence of items that require spatial thinking on New York State's end-of-course exam for high school Earth Science. Analyzing all items across 12 exams (1,016 items total), we find abundant instances of spatial concepts, spatial skills, and spatial representations, with 63.1% of the items being coded into one or more spatial categories. In an associated pilot study of item difficulty on one exam, we find that students on average scored lower on items that we had coded as spatial than on items we had coded as nonspatial. In the short run, these findings should motivate Earth Science teachers to attend more deliberately to fostering spatial thinking in their instruction. In the long run, findings such as these can be used in crafting targeted professional development based on an analysis of what types of items an individual teacher's students have found to be difficult. *© 2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-104.1]

Key words: spatial, representation, assessment

MOTIVATION FOR THE STUDY AND RESEARCH QUESTIONS

Spatial thinking is an important tool in the geoscientist's approach to make meaning from complex Earth Systems. Thus finding ways to foster and assess spatial thinking is of interest to the geoscience education community. Informal inspection across many years of New York State's end-of-course exam for high school Earth Science (the "Earth Science Regents Exam") had suggested to us that it contained numerous items that required spatial thinking and that an interesting variety of different kinds of spatially demanding challenges were presented. For this reason, we undertook an analysis of previous years' exams to identify, categorize, and quantify the types of spatially demanding items that appear on the exam. Our research questions were:

- In the main study: What types of spatial thinking are evident in the items on the New York State Earth Science Regents exam? How abundant are items associated with each of the identified types of spatial thinking?
- In the pilot study: Are items identified as "spatial" significantly more difficult for students than nonspatial items?

Our intent was that, in the short run, these findings would motivate Earth Science teachers to attend more deliberately to fostering spatial thinking in their instruction, and would steer instruction towards the most relevant types of spatial thinking. As a by-product of the research, we generated a database of items (included in the online version of the journal and available at: http://dx.doi.org/10.5408/13-104s1 and http://dx.doi.org/10.5408/13-104s2) that can be searched by topic and spatial thinking category to generate student activities or formative assessments that exercise targeted spatial skills, concepts, or representation types. Although higher test performance is the "hook" to attract instructors and students to attend to spatial thinking, based on our own experience as instructors and the literature reviewed below, we approached the study with the expectation that improving spatial thinking could strengthen students' ability to think deeply about Earth processes and understand Earth Science concepts.

In the long run, we envision that analyses such as these can be used to shape individualized, data-guided professional development in which teachers are supported in strengthening the specific skills and practices with which their students have been struggling. Although we are sensitive to the possibilities of misuse of standardized test data, our position is that if school systems are moving inexorably in this direction anyway, then the geoscience education community would be well-advised to leverage this trend to foster the abilities and habits of mind that are important in our field. To try out our ideas in a professional development context, we offered a series of teacher workshops on spatial thinking (Kastens et al., 2012) through the Earth2Class professional development program at Lamont–Doherty Earth Observatory at Columbia University in New York. Based on feedback from the workshops, we

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then wrote a series of three articles for practitioners describing instructional strategies targeting three of the spatial thinking challenges that we commonly found on the Regents exam (Kastens and Passow, 2012; Passow and Kastens, 2013; Roessel et al., 2013).

CONTEXT

In this section, we offer an operational definition of spatial thinking, and review the literature showing (a) that spatial thinking is important in science, especially Earth Science; (b) that spatial thinking can be improved; and (c) that spatial thinking tends to be undertaught in U.S. schools and, thus, may be "low-hanging fruit" for the improvement of Earth Science education. We also describe the New York State Regents course and exam, upon which our study is conducted.

Spatial Thinking Is Important in Science, Especially Earth Science

Spatial thinking in the context of Earth Science involves envisioning, manipulating, or drawing meaning from the position, shape, orientation, trajectory, or configuration of objects or phenomena, or groups of objects or phenomena. The ability to create and extract insights from 2D spatial representations—including maps, diagrams, profiles, block diagrams, and stratigraphic sections—is part of spatial thinking. Envisioning and reasoning about 3D structures such as folded rocks, and 3D processes such as the orbital causes of seasons, eclipses, and tides, is also part of the mix. Spatial thinking uses the properties of space as a vehicle for structuring problems, for finding answers, and for expressing solutions (National Research Council [NRC], 2006).

The National Research Council (2006) has published a comprehensive report on the importance of fostering spatial thinking in K–12 education. The report compiles evidence from multiple domains of science and geography, considering the role of spatial thinking in great accomplishments at the frontiers of knowledge, and in more ordinary accomplishments in science classrooms. More recently, Uttal and Cohen (2012) compiled evidence that spatial ability can serve as a gatekeeper skill for entry into the STEM education and workforce pipeline. The National Science Foundation's education directorate has funded a major science of learning center, The Spatial Intelligence and Learning Center (SILC), which has selected geoscience as one of its major content areas. Kastens and Ishikawa (2006) articulated a taxonomy of spatial thinking in geosciences including recognizing, describing, and classifying the shape of objects such as fossils and minerals; describing the position and orientation of objects such as faults; making and using maps to organize, archive, and convey information; envisioning processes in three dimensions; and using spatial-thinking strategies to think about nonspatial phenomena. Kastens (2010) makes a further linkage between geoscience education and the literature on object versus spatial visualization (Kozhevnikov et al., 2005). The 2009 annual conference of the Geological Society of America devoted a special session to "Spatial Skills in the Geosciences" (Karabinos, 2009; Libarkin et al., 2009; Riggs, 2009; Shipley, 2009), and an NSF-funded project to create a "Synthesis of Research on Thinking and Learning in the Geosciences" selected spatial thinking as one of four focus areas (Kastens et al., 2009). Some branches of geosciences are more spatially demanding than others (Dyar, 2012); in particular, Liben and Titus (2012) and Liben et al. (2011) analyzed the close relationship between spatial thinking and field structural geology tasks.

Spatial Performance Can Be Improved

Research has documented large individual differences on a wide range of spatial tasks (Liben, 2006). Many students struggle with such thinking, as documented so vividly in the classic film, *A Private Universe* (Harvard Smithsonian Institution for Astrophysics, 1987), which shows both high school students and newly minted Harvard graduates stumbling through flawed explanations of the causes of seasons and lunar phases.

Early efforts to improve performance on spatial tasks met with limited success, finding either little improvement or improvement that did not transfer well to related tasks (e.g., Liben and Golbeck, 1984; Sims and Mayer, 2002). Folk wisdom and stereotypes have reinforced the impression that some people are just not good at spatially demanding tasks such as reading maps. More recent research has shown, however, that spatial thinking can be improved through instruction and practice (Uttal et al., 2013). Sorby (2009; Sorby and Baartsmans, 2000) has improved the grades and retention rate of spatially challenged undergraduate engineering students by offering an optional semester course in spatial visualization. Piburn et al. (2005), Titus and Horsman (2009), and Ormand, et al. (2013) have documented student improvement on psychometric tests of spatial ability following spatially intensive college geology courses.

Spatial Thinking Is Undertaught in U.S. Schools

Gohm and colleagues (1998) compared high school students gifted in spatial ability with a mathematically gifted sample. The students gifted in spatial ability, or high-spatial students, were less likely to be recognized by their schools as accomplished, received less college guidance from the school, and achieved lower levels of academic and career success. There is also a gender equity aspect to schools' lack of attention to spatial thinking. On several well-studied spatial abilities measures, boys and men tend to outperform girls and women. The causes of this discrepancy are controversial, but the data are robust (Linn and Petersen, 1986; Liben, 2006), and spatial thinking may have been a contributing factor to females' historically low participation in science. Virtually every school in America offers remediation for students who struggle with reading, and those programs are disproportionately populated by boys. Almost no schools offer remediation in spatial thinking, the cognitive skill set disproportionately difficult for girls. In other words, both high-spatial and low-spatial children are ill-served by schools' lack of attention to spatial thinking.

At the level of the classroom teacher, experienced science teachers may intuit that visual or spatial thinking is important, but they rarely offer specific instruction in strategies to master the necessary techniques. Although the "Learning to Think Spatially" report (NRC, 2006) discussed spatial thinking in science, geography, and daily life, the impact on teachers and teacher preparation programs has been mainly in geography (e.g., Geography Education National Implementation Project, n.d.). One science teacher preparation textbook (Baker and Piburn, 1997) included an excellent chapter on "Spatial Science," but that book is now out of print and this theme has not carried forward into current texts for preservice teachers.

The New York State Earth Science Course and Exam

New York State Education Department's "Physical Setting: Earth Science" course (also known as "Regents Earth Science") is a comprehensive course covering the solid Earth, atmosphere, hydrosphere, and selected topics in space science (New York State Education Department [NYSED], n.d.[a]). A state-set Earth Science exam has been administered to students in high schools since 1941, and to accelerated students in middle schools since the late 1980s. In 2011–2012, 161,637 students took the exam, with a 73% passing rate (NYSED, 2013).

The exam comprises a three part written test (85%), plus a performance test (15%). The written test comprises 50 multiple choice questions and either 34 or 35 constructed response items. Before a student can take the exam, the teacher must certify that the student has completed a minimum of 1,200 minutes of laboratory experiences. Past exams are made available in their entirety through the Department of Education website (NYSED, n.d.[b]), and these items are widely used by teachers across the nation to create tests and assignments. A distinctive feature of the exam is that students are provided with a 16-page booklet of reference materials (The Earth Science Reference Tables, or ESRT), including geological and landform maps of New York, plate tectonic and ocean current maps of the world, rock and mineral identification keys, and so forth (NYSED, n.d.[c]). Experienced Earth Science teachers have students work with these reference tables constantly throughout the year to build familiarity with the representations, including spatial representations, that will be needed to answer exam items.

Regents exams are developed in accordance with a standardized protocol (New York State Office of State Assessment, 2013). Test items are created based on standards and test specifications approved by the Board of Regents. NYSED solicits item writers from classroom teachers, who attend workshops about how to produce acceptable items. Once item writers submit their contributions, these are edited at NYSED and, if appropriate, suitable diagrams are created. Then another committee of teachers and NYSED staff review the content, advise on special issues/populations, and assemble field test forms. Following protocols to ensure security of field tests, tests are administered by selected schools. Field test results are analyzed to estimate reliability and generalizability. Field test statistics and test specifications guide selection of items used in creating the operational tests.

A few previous researchers have analyzed aspects of the Regents Earth Science course and exam. Ladd (1972) and Orgren and Doran (1975) studied the introduction of a revised and more inquiry-oriented version, and documented changes in both the curriculum and associated teaching practices. Contino (2012) examined alignment among the June 2010 exam, the National Science Education Standards (NRC, 1996), and the New York State Physical Sciences/Earth Science Core Curriculum document. She found that the exam and the curriculum document were "slightly aligned," with the curriculum document calling for higher cognitive levels than were tested on the exam. Contino and Anderson (2013) analyzed the relationship between teachers' enacted curriculum and the Regents exam and Core Curriculum, finding that experienced teachers included content in their lessons that was not addressed in the Core but was often found on the Regents exam.

METHODS

Materials

The Physical Setting/Earth Science exam is offered three times per year in January, June, and August. We worked with all of the exams for 2008, 2009, 2010, and 2011, for a total of 12 written exams. Each written exam has either 84 or 85 items, and all items have been released, so we analyzed a total of 1,016 items. We did not work with the separate, hands-on "lab practical exam," although we note that two of the tasks (epicenter location and constructing an elliptical orbit) would fall within our criteria for spatial thinking. All of the exams analyzed are available for download at http://www.nysedregents.org/earthscience/, along with students' answer booklet, teachers' scoring key, and rating guide. We analyzed the items alongside the Earth Science Reference Tables that were current when each exam was administered: using the 2001 version of the ESRT in analyzing 2008 and 2009 exams, and the 2010 ESRT for the 2010 and 2011 exams.

Coding by Topics

All items on all 12 tests were coded by topic, using four categories: Geosphere, Hydrosphere, Atmosphere, and Space. Topic coding was done by author M.J.P., informed by his 25 years of experience working with this exam as a teacher, item writer, and teacher-educator. The Geosphere category includes surface and internal processes and structures of the solid Earth, as well as geological history. Geography topics, such as latitude and longitude and topographic map reading, were also coded as Geosphere. Hydrosphere includes liquid water, ice, and the water cycle (but not clouds). Atmosphere includes global circulation, weather (including clouds), and climate (including paleoclimate). The Space category is dominated by questions about the Earth–Sun–Moon system, but also includes items about other planets, stars, and cosmology. Items that might fall into two categories were coded based on where in the curriculum the topic is typically taught by Regents Earth Science teachers. For example, precipitation is part of the water cycle, but is typically taught as an aspect of weather and climate, so was coded as "Atmosphere" rather than "Hydrosphere." Weathering and erosion are typically taught as part of the rock cycle, so were coded as "Geosphere." Author K.K. did a second coding by topic of two exams (16.7% of the items) and, after training, the intercoder agreement was 93.5%.

Coding by Spatial Thinking Attributes

We were not aware of any prior analysis of the spatial elements of assessment items, so we had to begin by finding or developing a set of coding categories, definitions, and examples. We considered the spatial categories used by Kastens and Ishikawa (2006) to describe the spatial thinking of geoscience professionals, the geographers' spatial taxonomy as summarized by the National Research Council (2006), and the system of "spatial concept perspectives" assembled by the TeachSpatial project (TeachSpatial, n.d). We also consulted the cognitive science literature on spatial thinking, which provided descriptions of additional specific spatial skills (e.g., Downs and Liben, 1991; Hegarty and Waller, 2004).

Finding that none of these were exactly suited to our needs, we allowed the coding themes and categories to emerge from the data, while remaining faithful to the spirit of the prior taxonomies. An important overarching decision was to code for three broad categories—spatial concepts, spatial skills, and spatial representation. An item could then receive multiple subcodes, either within a broad category or in multiple broad categories. Another foundational decision was that we did not code for metaphorical uses of spatial thinking, in which space is used to represent an inherently nonspatial attribute (e.g., temperature or salinity), a category considered spatial thinking by Kastens and Ishikawa (2006) but not by all readers. This was a conservative choice, insofar as it results in a lower percentage of items being coded as spatial than would otherwise be the case.

Developing the coding schema required numerous iterations of coding, comparing, discussing, and reconciling. All items were coded for spatial attributes by two authors, K.K. and L.P. Differences were resolved by discussion. Early in the process, reconciling discrepancies often involved adding categories or modifying or clarifying definitions. After the coding schema stabilized, the interrater consistency between the two coders was 89.5%. We then recoded the earlier-coded exams to be consistent with the later-coded exams. As the coding schema was an outcome of the project, it is described in the Results section.

Development and Affordances of the Database

After the codings were finalized, the data for each item were entered into a searchable database built in FileMaker Pro. The record for each item includes the test date, item number, and presence or absence of each of the spatial and topic codes. The item prompt (both text and graphic, if any), the correct answer from the answer key, and any additional text or graphic provided on the students' answer sheet were also entered into designated fields of the database.

We used the database in two ways: first, to generate the data analyzed for this study, and second, to develop hands-on activities around specific spatial thinking challenges for use in our professional development series. The database is available in the online version of the journal and at http://dx.doi.org/10.5408/13-104s2 for use by other researchers or curriculum developers.

Pilot Study of Spatial versus Nonspatial Item Difficulty

Our intended study was about the abundance of spatially demanding items. However, in the course of the study, an opportunity arose to examine a sample of student results for item difficulty. We had item level data (percentage correct for each item) from 26 schools in one geographic region for the June 2010 exam. We view this as a feasibility study done on a convenience sample, rather than as definitive data. We present these findings to encourage future research, and to spur the collection and archiving of data in a form that will facilitate such studies on a statewide scale.

RESULTS

We present, first, a description of the range of types of spatial thinking present in the Regents exam, followed by an analysis of the abundance of the various spatial elements, and finally a glimpse at the difficulty of spatial versus nonspatial items.

Categories of Spatial Thinking

The types of spatial thinking that we found in the Earth Science Regents exam are defined briefly in Table I. The full coding schema, suitable to be used or adapted for future research studies, is included in the supplemental material (available in the online version of the journal and at: http://dx.doi.org/10.5408/13-104s3). Spatial elements fall in the broad categories of Spatial Concepts, Spatial Representations, and Spatial Skills.

Within Spatial Concepts, the first several subcodes deal with where something is located, either relative to a frame of reference or relative to something else: Position (SC-Po), Configuration (SC-Cn), Distance (Ds). The next several subcodes deal with changes of position over time: Motion (SC-Mo), Speed (SC-Sp), and Trajectory (SC-Tr). Direction (SC-Dr) can refer to either a static position (e.g., northern New York) or a dynamic motion (e.g., a northward flowing stream). After that, are subcodes dealing with size: Size (SC-Sz), Volume (SC-Vl), and Area (SC-Ar); followed by subcodes dealing with shape: Shape (SC-Sh, Texture (SC-Tx). Angle (SC-An) can refer to either shape (e.g., in a crystal) or location (e.g., degrees above the horizon of a star). In Regents Earth Science, Gradient (SC-Gr) is most commonly about the shape of the Earth's surface, but the subcode is defined broadly enough that variation across space in other attributes could also be included. The final two subcodes take a more Earth Systems perspective: Global interconnection (SC-GI) and Cycle (SC-Cy).

Items coded in the broad category of Spatial Representations require students to interpret process or structure from some kind of visual representation in which at least one of the dimensions of the paper is used to represent a spatial dimension in the real Earth System. Maps (SR-Mp) and Cross-sections/Profiles (SR-Pf) are both two-dimensional representations, distinguished by whether the two dimensions are parallel to the Earth's surface (SR-Mp) or perpendicular (SR-Pf). Block diagrams (SR-Bd) represent three Earth dimensions, while Graph of Y versus Distance (SR-Gd) represents a single Earth dimension. Visual representations of the solar system are common on the Regents exam, and do not fit cleanly into the categories above, so are given their own subcode (SR-SS). Items with

TABLE I: Coding categories.

Spatial Concepts (SC)
Position (SC-Po). Where something is (in space, in the earth, on the earth's surface)
Configuration (SC-Cn). The relative position of two or more objects, attributes or phenomena.
Distance (SC-Ds). How far apart things are in or on the Earth.
Direction (SC-Dr). Where things lie or are going in relation to a frame of reference. Direction can refer to either a static position (e.g., northern New York State), or to a dynamic direction of motion (e.g., northward flowing stream).
Motion (SC-Mo). Change of position through space or in space. The path and direction of the motion may or may not be specified.
Speed (SC-Sp). Speed is distance/time and therefore can sometimes be spatial (but often is not). Speed does not include direction (i.e., it is scalar).
Trajectory (SC-Tr). Trajectory refers to motion along a path. If there is no path specified, code simply as "motion." Path can be straight or curved.
Angle (SC-An). The rotational space between two lines or planes. One of the "planes" can be the Earth's surface.
Size (SC-Sz). How big or small something is (without a connotation of one-, two-, or three-dimensional and with the caveat that size must be germane to the Earth process[es] being probed).
Volume (SC-Vl). The amount of three-dimensional space an object (or a void) occupies.
Area (SC-Ar). The amount of two-dimensional space an object occupies.
Shape/morphology (SC-Sh). The distinctive quality of the outline or external form of an object or landform. Counted only if shape is germane to Earth process being probed.
Texture (SC-Tx). Microtopography (e.g., glacial grooves). Code if texture causes or is caused by an Earth process being probed, not if purely descriptive.
Gradient (SC-Gr). Question requires thinking about a situation in which an Earth attribute varies systematically across space.
Global interconnection (SC-GI). Question requires thinking about how processes in one part of the globe are impacting or can impact processes or observable attributes in other parts of the globe.
Cycle (SC-Cy). An Earth material moves through space and eventually returns to its original reservoir (e.g., rock cycle, water cycle) OR a spatial attribute (e.g., water level along coastline) varies over time with a regular period (e.g., tides).
Spatial Representations (SR)
Classify as spatial if the student has to interpret processes or structures from a spatial representation, including:
Map (SR-Mp). Representation uses two dimensions of the paper to depict two spatial dimensions of Earth, both horizontal.
Cross-section/Profile (SR-Pf). Representation uses two dimensions of paper to depict a slice perpendicular to the Earth's surface.
Block diagram (SR-Bd). Representation uses space on the paper to depict three spatial dimensions of Earth.
Photograph (SR-Ph). Code as a spatial representation if size or another spatial concept can be observed in the photo and is probed by the question.
Graph of Y versus Distance (SR-Gd). Graph that has real-world distance as the independent variable (e.g., altitude, latitude, distance onshore or offshore), and any Earth attribute (e.g., temperature, seismic wave travel time, density, grain size, velocity) as the dependent variable.
Solar System Representation (SR-SS). Includes a view of celestial bodies (sun, moon, Earth, other planets) as seen across space.
Other representations (SR-O). Includes other representations in which dimensions of the paper represent dimensions of the Earth system.
Spatial Skills (SS)
Perspective taking (SS-PT). To answer the question, student needs to envision how something would look from a viewpoint other than that currently occupied by the student.
Visual penetrative ability (SS-VPA). The student needs to envision or imagine the inside of a volume when only the exterior is shown (Kali and Orion, 1996).
Mental animation (SS-MA). Student needs to or would benefit from envisioning that objects are moving or deforming, and how they are moving or deforming.
Sequencing (SS-S). Student needs to use spatial information to unravel the order in which events occurred.
Describe (SS-D). Student needs to give an account in his or her own words about a spatial relationship, or use spatial terms to tell about an Earth phenomenon.
Representational correspondence (SS-RC). Student must transfer information from one spatial representation to another, or combine information from multiple spatial representations, or distinguish between (compare and contrast) similar representations (Liben, 1997).

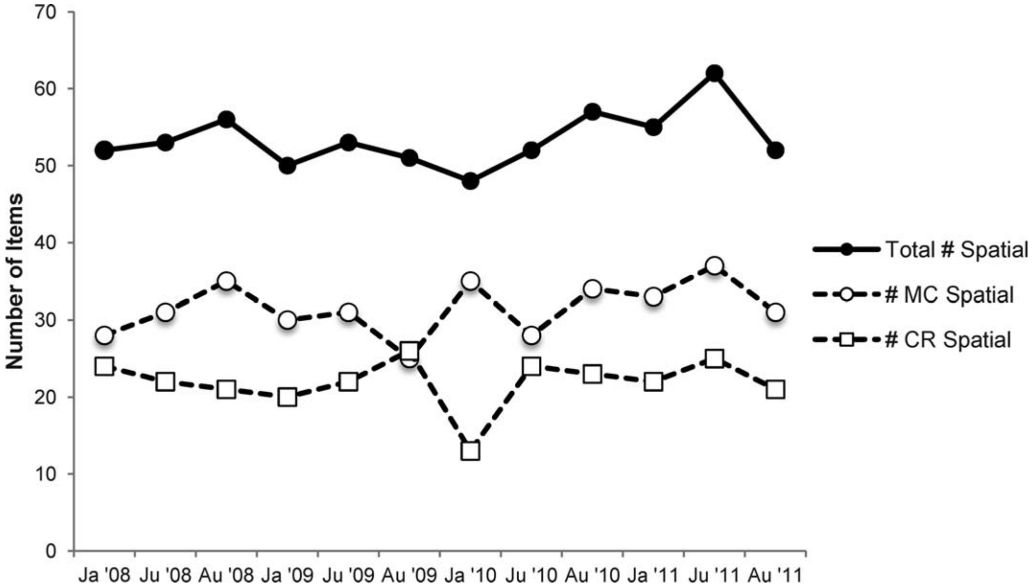


FIGURE 1: The abundance of spatial elements has varied somewhat from exam to exam. Considering that the exam makers have not explicitly targeted spatial thinking as a assessment goal, however, the abundance of spatial items seems impressively consistent. Each exam includes 50 multiple choice (MC) and 34 or 35 constructed response (CR) items.

photographs were only coded as spatial (SR-Ph) in cases where the question required using spatial information (e.g., size or shape) obtained from the photograph.

The Spatial Skills category was more heavily influenced by the prior literature on spatial thinking than were the SC or SR categories. Perspective-taking (SS-PT), mental animation (SS-MA), and representational correspondence (SS-RC) have long been studied by cognitive scientists (Linn and Peterson, 1986; Downs and Liben, 1991; Hegarty, 1992; Liben, 1997), and visual penetrative ability (SS-VPA) was thoroughly explored by previous geoscience education researchers (Kali and Orion, 1996; Titus and Horsman, 2009). Therefore we looked for—and found—these skills being exercised in Regents Earth Science items. The two coding categories that emerged from the data rather than the prior literature were Describe (SS-D) and Sequencing (SS-S).

We also found items that look or sound spatial at first glance, but that do not actually require students to think spatially. For example, in the January 2011 exam, question 26 is "Which pie graph correctly shows the percentage of elements by volume in the Earth's troposphere?" that includes the spatial term "volume." However, the solution requires merely looking up a value in the Earth Science Reference Tables and does not exercise the student's understanding of the spatial attribute of volume. Such items were not coded as spatial. See the full coding schema in the supplemental material (available in the online version of the journal and at: http://dx.doi.org/10.5408/13-104s3) for further detail on exclusion criteria.

Abundance of Spatial Elements

Overall Abundance

Across all 12 exams, 63.1% (641 of 1,016) of items contain at least one spatial element. Remarkably, the fraction of spatial items is virtually identical among multiple choice items 63.0% (378 of 600) and constructed response items 63.2% (263 of 416), and the abundance of spatial elements has not varied substantially from exam to exam over time (Fig. 1).

If an item is spatial at all, it is likely to have more than one spatial subcode. Most spatial items have three, four, or five subcodes, with the most codes per item being 12 (for one item only). Figure 2 shows examples of items with a moderate (5) and large (9) number of spatial subcodes.

Abudance of Spatialness by Geoscience Discipline

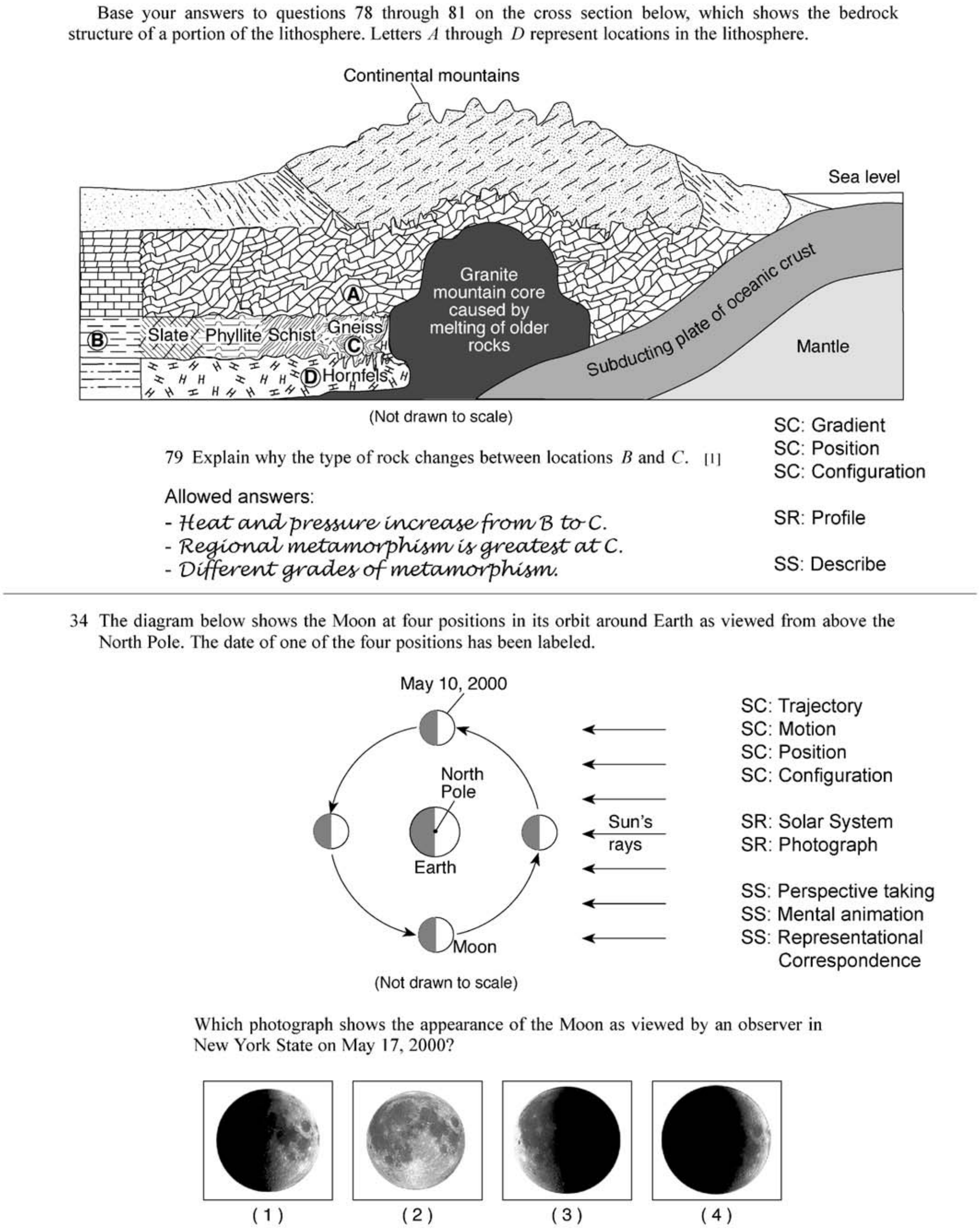
Regents exam items are not evenly distributed across the Geoscience subdisciplines (Fig. 3, upper). On the 12 coded exams, approximately half (49%) of the items concerned the solid Earth (geosphere). Astronomy (27%) and the fluid Earth (19% atmosphere and 5% hydrosphere) each comprised approximately a quarter of the items.

Astronomy items are the most spatial, with 73% of such items having one or more spatial elements (Fig. 3, lower). Hydrosphere items are the least spatial (53%). Atmosphere (62%) and geosphere (60%) are intermediate in their spatialness.

Abundance of Coded Spatial Elements

The most common spatial concepts are configuration, position, motion, and direction (Fig. 4, upper), each of which appeared in more than 20% of exam items. The elements that lend themselves to a quantitative treatment (distance, angle, gradient, speed, size, volume, and area) are less abundant.

Spatial representations occurred in three venues: on the item prompt, on the answer sheet, and on the Earth Science Reference Tables. In some cases, students had to refer to multiple representations to answer the item. The spatial



Base your answers to questions 78 through 81 on the cross section below, which shows the bedrock structure of a portion of the lithosphere. Letters *A* through *D* represent locations in the lithosphere.

79 Explain why the type of rock changes between locations *B* and *C*. [1]

Allowed answers:
- *Heat and pressure increase from B to C.*
- *Regional metamorphism is greatest at C.*
- *Different grades of metamorphism.*

SC: Gradient
SC: Position
SC: Configuration

SR: Profile

SS: Describe

34 The diagram below shows the Moon at four positions in its orbit around Earth as viewed from above the North Pole. The date of one of the four positions has been labeled.

SC: Trajectory
SC: Motion
SC: Position
SC: Configuration

SR: Solar System
SR: Photograph

SS: Perspective taking
SS: Mental animation
SS: Representational Correspondence

Which photograph shows the appearance of the Moon as viewed by an observer in New York State on May 17, 2000?

FIGURE 2: Example items, annotated with their spatial subcodes. Both examples shown have subcodes in all three categories.

representation category was dominated by maps, profiles, and solar system diagrams (Fig. 4, center). Block diagrams, which have featured prominently in geocognition research (Kali and Orion, 1996; Titus and Horsman, 2009), were only present in 4% of the items examined.

The most common spatial skill by far was mental animation, followed by representational correspondence and perspective taking (Fig. 4, lower). Describe was almost as common as perspective taking, which is notable since this code was only applied to constructed response questions. Sequencing shows up on virtually every exam, usually as one diagram with a cluster of related questions, but doesn't rise to a high statistical abundance. Visual penetrative ability is rarely assessed (<1% of items) on the Earth Science Regents.

Difficulty of Spatial Elements

For the June 2010 exam, the students in our 26 sampled schools scored lower for those items coded as spatial than they did for those items coded as nonspatial (Fig. 5): the mean percentage correct for spatial items was only 66.1%, whereas the mean percentage correct for nonspatial items was 72.8%, a statistically significant difference (2-tailed *t*-

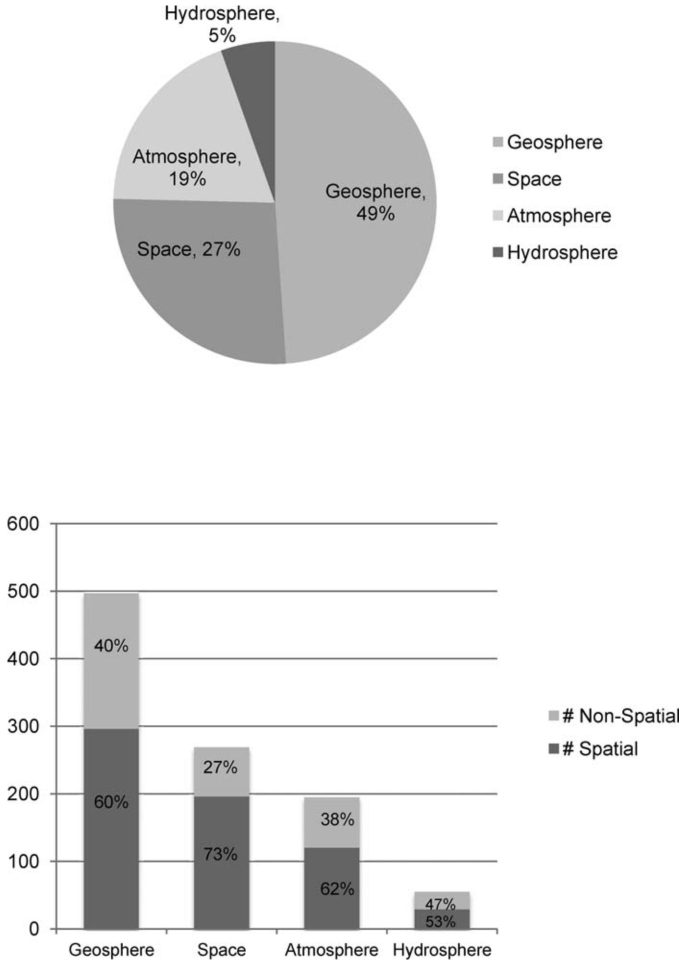


FIGURE 3: (Upper) The distribution of items by topic on the 12 examined exams. Astronomy and fluid earth (atmosphere + hydrosphere) each command approximately a quarter of the items, with solid Earth filling out the remaining half. (Lower) Abundance of spatial elements by geoscience subdiscipline. Spatial and nonspatial items are relatively more frequent in astronomy items and relatively less frequent in hydrosphere than on the exam as a whole.

test, $p = 0.04$). Focusing on the items that had the lowest percentage correct, 9 out of 10 of those items were spatial.

We also examined the difficulty of the items by spatial code. Although the item-to-item variability of student scores within a given code is highly variable, five spatial codes stood out as more difficult than the other spatial elements (Table II). These are the spatial concepts of Gradient and Trajectory, the spatial skills of Perspective Taking and Describing a spatial situation in one's own words, and the Solar System spatial representations.

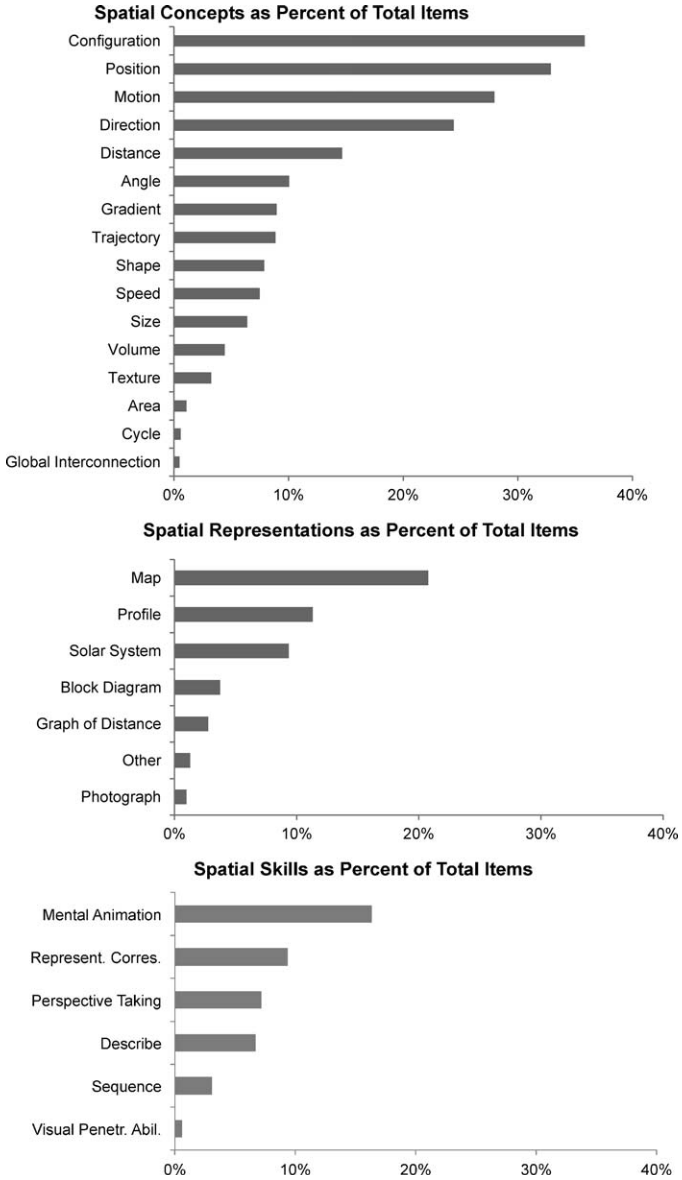


FIGURE 4: Graphs show the percentage of analyzed exam items that fell within each spatial coding category, with individual items allowed to fall in multiple coding categories. (Upper) Among spatial concepts, configuration, position, motion, and direction were most abundant, occurring in more than 20% of items. (Middle) Map was by far the most abundant spatial representation. (Lower) Spatial skills, as we defined them, are not incorporated into test items as often as spatial concepts or spatial representations.

DISCUSSION

Abundance of Spatial Elements

The abundance of spatial elements, across all exams and both item types, is a striking aspect of our findings, and confirms the urgency of attention to spatial thinking among those responsible for planning and implementing Earth Science instruction. In considering this finding, the reader should keep in mind that our criteria for categorizing items as spatial were conservative, in that we excluded some items that involved "spatial" but not "thinking," and also items involving "spatialization" of attributes that are not inherently spatial.

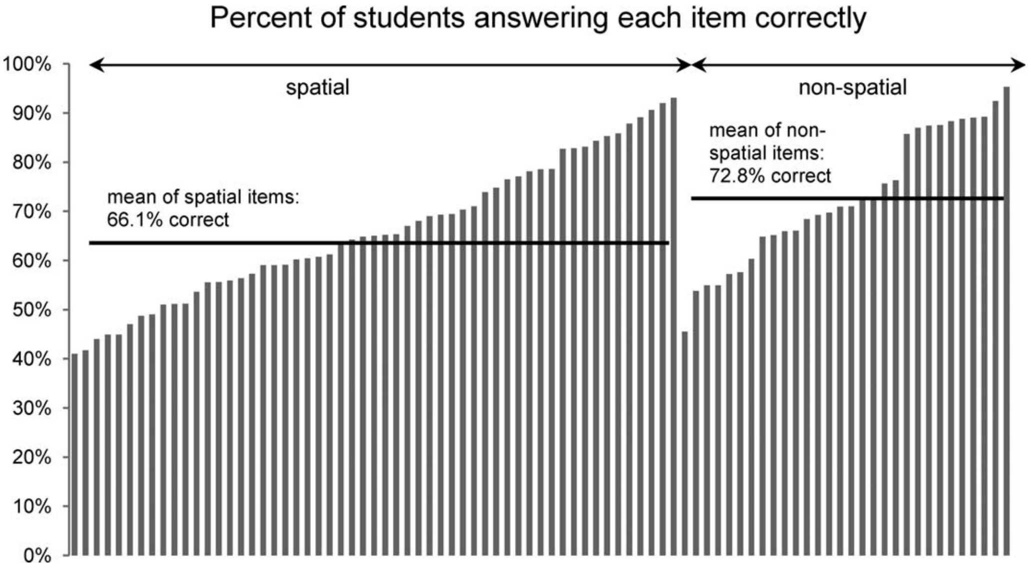


FIGURE 5: Each item on the June 2010 Earth Science Regents exam is represented by a bar; the height of each bar shows the percentage of the sampled population that answered that item correctly. Items coded as spatial are in the left cluster, and items coded as nonspatial are in the right cluster. Within each cluster, items are arrayed by item difficulty. On average, students scored lower on the spatial items than on the nonspatial items.

The consistency of the spatial component across exams suggests that the exam creation and vetting system is effectively and consistently producing exams that test for proficiency with spatial concepts, skills, and representations. This is true even though the guidance to item writers does not include specific mention of spatial thinking. This finding can be understood if the exam-writing process is viewed as a social construction created by a community of practice (Lave and Wenger, 1991) who share a common set of values.

The distribution of items by geoscience topic (Fig. 3, upper) was not the focus of our project, but is an interesting by-product. The observed distribution across all exam items is close to 50% Solid Earth, 25% Astronomy, and 25% Fluid Earth. This distribution may be of interest to teachers for course planning. Considering how important water quality and quantity issues are likely to be in the 21st century, the fraction of items devoted to hydrosphere (5%) seems to us to be too low.

The spatial concepts that lend themselves to a quantitative treatment (distance, angle, gradient, speed, size, volume, and area) are less abundant, which is consistent with the generally qualitative approach taken in precollege Earth Science instruction. The examples in the "Process Skills: Mathematical Analysis" section of the Physical Setting/Earth Science Core Curriculum document (NYSED, n.d.[a]) do specifically mention some quantitative spatial concepts, including gradient, shape, speed (velocity), size, and volume. However, our analysis shows that these are not as frequently assessed as some of the more qualitative spatial concepts.

No geoscientist will be surprised to find that SR:map is the most frequently assessed spatial representation, followed by SR:profile. In a science in which experimental manipulations are difficult or impossible for many important questions, geoscientists rely heavily on natural experiments in which a causal factor varies across space (Kastens and Rivet, 2008), and on the technique of trading space for time. Maps, profiles, and cross-sections are the tools by which such causally significant spatial patterns are conveyed, discussed, and reflected upon.

Among the spatial skills, the high frequency of mental animation (16% of all items analyzed, the most abundant

TABLE II: Difficult spatial elements.

	Number of Items	Mean (SD) % Correct	Difference From Mean
All spatial items	55	66.1 (14.3)%	
SC: Trajectory	7	52.3 (5.3)%	−13.8%
SR: Solar System	6	57.4 (14.7)%	−8.6%
SC: Gradient	7	60.8 (10.3)%	−5.3%
SS: Describe	7	61.6 (10.7)%	−4.5%
SS: Perspective Taking	5	61.8 (11.8)%	−4.3%

spatial skill) reflects the prominence of dynamic processes in modern geosciences. It would be interesting to see whether the abundance of this spatial skill was lower in the Regents exams from the pre–plate tectonics era. Representational correspondence (comparing or combining information from two or more spatial representations) is the second most common spatial skill (9% of all items). This finding aligns with a study of the types of spatial tasks in elementary school geography workbooks, in which representational correspondence tasks far outnumbered production tasks, comprehension tasks, and metarepresentational tasks (Kastens et al., 2003). Visual penetrative ability is rarely assessed (<1% of items) on Regents Earth Science exams, although it is highly valued among geoscience professionals, and college geoscience professors strive mightily to develop this skill (e.g., Titus and Horsman, 2009).

Difficulty

Our limited data set on student performance by item tells us that items requiring spatial thinking are not only common on the Earth Science Regents exams, but are also difficult for students. Particularly persuasive is the spatial/nonspatial ratio on the hardest items: of the 10 lowest-scored items on the June 2010 exam, 9 out of 10 were spatial. Both the abundance and challenge level of the spatial items are reasons for devoting more explicit attention to this form of thinking in teacher professional development and instructional materials design.

The spatial elements that emerged as being exceptionally difficult for our test population on the June 2010 exams resonate with the experience of Earth Science teachers and align with the psychological and education research literature. Gradient (SC-Gr) is one of the few concepts in Regents Earth Science exam that is regularly tested at a quantitative rather than qualitative level, with students being asked to calculate a gradient. Trajectory (SC-Tr) requires thinking about a dynamic system, with more constraints or influencers on the motion than for those items coded as merely SC-Mo (motion). Perspective taking (SS-PT) has been shown to be difficult by research in cognitive science (Downs and Liben, 1991). Describe (SS-D) is always a production task that requires students to generate spatial language from scratch, rather than choosing from among provided choices. Constructed response items in general tend to be more difficult than multiple choice items, and that seems to be the case for the Earth Science Regents (June 2010 CR items: 63.1% correct; MC items: 72.2% correct).

The fact that students have access to the Earth Science Reference Tables throughout the school year and on the exam allows the test constructors to include harder items than they could otherwise use, especially around the use of spatial representations. For example, item 17 from the January 2011 exam asks "In which New York State landscape region have fossilized footprints of *Coelophysis* dinosaurs been found in the surface bedrock? (1) Allegheny Plateau, (2) Tug Hill Plateau, (3) Hudson-Mohawk Lowlands, (4) Newark Lowlands." Answering this question requires a multistep chain of reasoning that involves coordinating among several different kinds of spatial and nonspatial representations, including selecting the appropriate representations from the 16-page ESRT. The student must first consult the ESRT timeline of "Geological History of New York State" to ascertain that *Coelophysis* lived in the Triassic Period, use the ESRT "Generalized Bedrock Geology of New York State" map to find the only area in New York with Triassic sediments, and then use the ESRT "Generalized Landscape Regions of New York State" map to determine that such sediments are found in the Newark Lowlands. This item was coded as SR: Map + SC: Position + SS: Representational Correspondence. Approximately one-third (208 of 641) of the spatial items used the ESRT.

How to Apply These Findings to Improve Earth Science Education

New York's use of the Earth Science Reference Tables can serve as a model for other states as they move towards developing assessments aligned with the Framework for K–12 Science Education (NRC, 2011) and the Next Generation Science Standards (NGSS). The *Coelophysis* example described above engages students in NGSS Practice 8: "Obtaining, evaluating, and communicating information." They must figure out what information is needed, extract that information from amid a cacophony of intellectually and visually distracting irrelevant information, and then assemble bits of information into a chain of reasoning.

The most important utility for these findings may be in motivating Earth Science teachers, curriculum developers, designers, and implementers of professional development to be more attentive and explicit about spatial thinking in instruction and assessment. A model for curriculum developers can be found in *Earth Science Puzzles: Making Meaning from Data* (Kastens and Turrin, 2010), in which instances of spatial thinking (along with temporal and quantitative thinking) are explicitly called out in the pedagogical content knowledge guide that accompanies each activity. A model for designers of teacher professional development may be found in a workshop series developed by the authors of this paper (Kastens et al., 2012). Materials from the workshops can be found on line at www.earth2class.org/er/vc. The ideas that were most enthusiastically received by the workshop participants have been shared through a series of practitioners' articles (Kastens and Passow, 2012; Passow and Kastens, 2013; Roessel et al., 2013).

New York has stated the intention to move towards a data-informed model of school improvement, in which data from New York's standardized tests are used to derive information relevant to design of curriculum, instruction, and professional development (Love, 2002; Murray-Wilson, 2009; Alliance for Excellent Education, 2010). At present, this effort is at the stage of building databases, debugging user interfaces, and setting up school-based inquiry teams to monitor performance data of selected groups of low-performing students. In the foreseeable future, however, we anticipate that patterns will emerge that students of some teachers do relatively well on some kinds of items and poorly on others. The most obvious patterns are likely to be content-based: for example, Ms. A's students do well on weather but poorly on rocks. We hypothesize that patterns will also emerge based on types of thinking processes, including quantitative reasoning and spatial reasoning. As such patterns emerge from the data analysis, professional development could support teachers whose students exhibit difficulties on items involving such skills.

In pointing out the potency of our findings for motivating Earth Science teachers, we wish to emphasize that although improving students' test performance may be the "hook" by which teachers are drawn to attend to spatial thinking, our claim in this paper is about far more than "teaching to the test." The overwhelming evidence that spatial concepts, spatial skills, and spatial representations abound in geosciences (Kastens and Ishikawa, 2006; Liben and Titus, 2012; Reynolds, 2012), and that geoscientists excel at spatial tasks (Hegarty, 2010) has persuaded us that improving Earth Science students' spatial proficiency will benefit them well beyond any single course or test.

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