SPATIAL THINKING: WHERE PEDAGOGY MEETS NEUROSCIENCE

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Abstract

Much of geographic education is a process of training students to think geographically when they look at a photo, map, or other spatial representation. Research on human cognition, however, has undergone a revolution in the past 20 years. Before the 1990s, human brain research consisted mainly of finding people whose brains had been damaged by strokes or in wars or industrial accidents, and measuring what kinds of "thinking" they could no longer do. Then, several new brain-scanning technologies made it possible to observe brain activity as people did various activities. That kind of research clearly shows that spatial thinking is a complex process. A skilled map reader appears to engage different brain structures in order to compare places, delimit regions, describe spatial patterns or transitions, recognize spatial associations, identify spatial hierarchies, and so forth. That fact has implications for curriculum development, educational materials design, and student assessment.
Key words: *analogy, education, map interpretation, spatial thinking, spatial association, region.*

Introduction

One of the most famous studies in psychology involved a railroad worker named Phineas Gage. This unfortunate man was the victim of a horrible accident. An unexpected explosion pushed a long iron bar through his head, destroying his left eye and part of his brain (Figure 1).

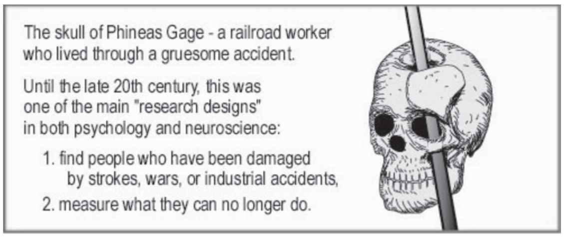

Figure 1. Brain-damaged individuals were the basis of brain research before the 1990s.

The bar landed more than a hundred meters away. The force of the explosion is an important part of the story, because the bar apparently passed through his head so fast that it sealed the broken blood vessels and sterilized the wound. As a result, he not only survived the accident, he lived another dozen years.

The accident, however, caused permanent brain damage. Psychologists were interested in observing Mr. Gage because the accident left him unable to do some things that he had been able to do before. The details of his life are easy to find on the internet. Of interest to geographic educators is the fact that he had difficulty remembering how to travel between familiar places.

Then, in the mid-1990s, scientists developed several new technologies for observing the human brain without injury or invasive surgery. These technologies made it possible to identify specific parts of the brain that appear to become active when people do particular kinds of thinking. Using these technologies – PET, fMRI, TCMS, TCI – literally thousands of studies have been done in the last fifteen years, in many different laboratories around the world.

Some of these studies looked at the process of *spatial sequencing* – mentally storing landmarks in proper order as you go toward a particular destination, such as from your house to your school. These studies reinforced one conclusion that people had drawn by observing Phineas Gage – the human brain seems to have a specific structure, located in the front of the brain, that is important in the process of spatial sequencing (see, for example, Histed and Miller, 2006).

For the past ten years, we have been reviewing neuroscientific studies and trying to find the ones that deal with spatial thinking. Specifically, we are looking for studies that identify the brain areas that appear to be active when people are thinking about places and relationships between places. One major conclusion from our review is that spatial thinking is more complex and more pervasive than previously thought. Until the late 1900s, educators commonly used the term "spatial intelligence," as if it were a single kind of thinking (Gardner, 1983). The new research, however, suggests that spatial thinking may actually be at least eight and perhaps as many as eleven distinct processes, which occur in different parts of the brain and involve different networks for memory. This fact is important for geographic educators, because these neurologic differences may be partly responsible for individual differences in performance on tests that involve interpreting a map or other geographic representation (Gersmehl and Gersmehl, 2006, 2007a, 2007b).

Problem of Research

Our major goal in reviewing this research was not just to understand what modern neuroscience has discovered about the human brain. Our major goal was to identify neuroscientific ideas that might help people design better geography lessons. That is what we were asked to do in this paper – to summarize a large amount of research about different kinds of spatial thinking.

During our preliminary review of the research, however, an unexpected event happened, "like a meteor falling out of the sky." That unexpected event was a new school that opened with five kindergarten and four first-grade classrooms. This school is located in a neighborhood of New York City called Harlem. The parents of the children in this school are predominantly African-American, and many of them live in public housing and have incomes far below the poverty line.

The administrators of this school asked us to help design some lessons in geography. At first, their concept of geography was little more than memorizing the names of places – countries, cities, mountains, rivers, and oceans. This narrow definition of geography is a common misperception, especially in the United States. We responded that we were not interested in that narrow task. Instead, we proposed to design lessons that focus on spatial thinking and rely on modern ideas of neuroscience. We suggested that lessons designed to "force" students to do spatial thinking may actually result in better memories of places and their relationships. Furthermore, we said, we would like to test a truly radical idea: perhaps a good geography lesson for very young children would also help them learn how to read and do mathematics better.

Research Focus

After a long discussion, the teachers and administrators in the school decided to try the approach that we described. We then prepared nine groups of lessons. Each group of lessons had its primary focus on a specific mode of spatial thinking. Each individual lesson featured a vocabulary list, and many of the lessons also included mathematical tasks, such measurement of distance or comparison of size. Copies of the first draft of these lessons (before revision) were included on the CD of the book *Teaching Geography* (Gersmehl and Gersmehl, 2008).

It is important to note that these lessons were offered to the school in draft form. As we discussed the lessons with teachers, we encouraged them to suggest modifications and to design other materials and activities to support the lessons. To assist in that process, one of the authors (or a City University graduate student, Adrienne Ottenberg) regularly visited the classrooms and talked with teachers nearly every week. In this way, the lessons were adapted by different teachers in different ways.

This procedure, of course, complicated the task of assessing the effectiveness of the lessons. At the same time, however, it also provided a broad range of ideas that could be examined. As a result, we cannot say at this time exactly which lessons would be most effective for an individual teacher. We offer them in this paper as illustrations and suggestions, not as proven products – because the primary goal of this paper is to provide a summary of the neuroscience research that is relevant to the task of designing geography lessons for very young children.

General Background

Before we begin the detailed review of neuroscience that is the core of this paper, let us make three general comments. The purpose of these comments is to relate our work directly to the title of the project that was described to us: *Problems of Education in the 21st Century*.

1. Our school in Harlem clearly illustrates one big problem in American education – the concentration of low-income families in particular geographical areas. Cities in the United States, like cities in many other countries, have neighborhoods with very different demographic and economic characteristics. As a result, some schools have mostly children of professional people who have college degrees and high income. Other schools are like our Harlem school – the children come from families with low income, little education, and often only one parent living with the child. These schools are difficult places for teachers, partly because teacher pay in the United States is sometimes linked with the test scores of their students. This is especially true in recent years, because schools are evaluated according to the rules of a law called No Child Left Behind. This has had an unfortunate consequence: good teachers often leave poor schools if they are offered a chance to teach in communities that have highly educated professional people. As a result, the schools in poor neighborhoods often have higher rates of teacher and student turnover. In a review of neuroscience research, we cannot address all of the problems of poverty and urban segregation, but at the same time we cannot pretend that these issues do not exist!

2. Our work with the Harlem school also illustrates another problem – the practical difficulty of conducting controlled experiments to test the effectiveness of new instructional materials. In a controlled experiment, several classrooms should be identical in every major respect <u>except</u> the nature of the instructional materials. The rooms should have similar size, equipment, and lighting. They should have similar numbers of students and similar instructional budgets. The students should have similar backgrounds, the parents should have similar income and education, and the teachers should have similar experience. Then, one could compare test scores of students that used the experimental materials and tactics with scores of students that were taught with other materials and approaches. The nature of our Harlem experience, however, makes that kind of "experimental design"

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difficult. For one thing, the simple fact that one school and its teachers volunteer to test some innovative materials means that the situations are not similar – the comparison would be between a volunteer school and one that was "forced" to be part of the experiment. This problem pervades every attempt to compare student performance in different schools. The differences are compounded by many other differences in class size, class schedule, teacher preparation, and so forth. As a result, it is exceptionally difficult to determine whether differences in test scores are the result of our lessons or the other complicating factors. In a review of neuroscience research, we cannot address all of the problems of educational research design, but at the same time we cannot pretend that these issues do not exist!

3. A third kind of problem occurs because children are changing. The same advances in technology that make brain scanning possible have also changed the lives of children. Today's young people have cell phones, computers, and many forms of electronic entertainment. They are engaged in modes of social networking that did not exist 20 years ago. They can use computers to search for information about almost any imaginable topic. But they also have little guidance in deciding what kinds of information are valid and what is best described as misinformation. In short, we no longer live in a world where a textbook with color photos is the most exciting part of a child's life. In a review of neuroscience research, we cannot address all of the problems of technological change, but at the same time we cannot pretend that these issues do not exist!

What can we do? We can look carefully at the one thing that we have studied over the past ten years – the research that deals with the ways in which human beings perceive, process, remember, and communicate geographic information. Modern neuroscience suggests that people perform these tasks in a number of different ways. In effect, different people can look at the same map and see different things in it.

Review of Research about Spatial Thinking

In this core part of the paper, we will briefly describe eight different modes of spatial thinking. We will summarize relevant neuroscientific research and then describe some of the teaching ideas that we suggested to the people in the Harlem school. Space will not permit us to examine the different ways in which some teachers modified these lessons, but it is important to repeat that different teachers often did the lessons in different ways in different classrooms.

Our goal in the Harlem school was to "practice what we preach," by trying to design instructional materials that focus on helping students improve their ability to do each of these eight different modes of spatial thinking:

1. **Spatial comparisons**. Skilled map readers compare places by examining maps that use symbols of different size, lines of different width, or areas of different color to represent quantities in different places. Neuroscience now knows that a small area of the brain above and behind the left ear is engaged when people compare many things, including the sizes of circles, the numbers of dots, the brightness of lights, or the loudness of sounds (Walsh, 2003; Pinel, et al. 2004; Hubbard, et al. 2005; Kadosh, et al. 2008). These conclusions are supported by several independent brain-scanning methods (Goebel, et al 2006). Quantitative comparisons like these, in turn, form the basis for mathematical reasoning (Venkatraman, Ansari and Chee, 2005; Zhou, et al. 2006). Some researchers have

explored the influence of language on quantitative comparison (Zebian, 2005); others have traveled to remote parts of the world in order to examine quantitative reasoning by pre-literate people (Pica, et al. 2004). Still others have explored the implications of these results for understanding age and gender differences in mathematical reasoning (Knops, et al. 2006; Pasnak, et al. 2009). After reviewing many of these studies, we think that the same principles may help geography teachers deal with individual differences in spatial performance. In that context, it is worth noting that the new neuroscience provides a scientific foundation for some cartographic principles that had been established many years ago on the basis of behavioral studies (Flannery, 1971; Provin, 1977).

The lessons that we developed for the Harlem school included several that dealt with the symbolic representation of size or amount. One lesson, for example, asked students to arrange models of the continents in order of size. They could then color the continents on a map, using the cartographer's rule that darker colors indicate larger quantities. Other lessons involved making marks to show the locations of desks in the classroom and then using words like crowded or empty to describe different parts of the resulting "map." Still others asked for verbal comparisons of rooms in the school – "the science room is bigger than our classroom; the office is smaller." In some classrooms, the students or teacher "invented" a unit of measurement that they called a "scholar." They defined a scholar as one student with outstretched arms. Several students could then stand in a line with their arms outstretched and their fingers touching and say something like "the science room is seven scholars wide." That is smaller than our classroom, which is nine scholars wide. All of these lessons are not just building vocabulary (for language arts) and number sense (for math classes). They are also helping to form the neural networks that in future years will allow more efficient processing of quantitative maps, such as dot maps of population or choropleth maps of life expectancy.

2. **Spatial influences (auras)**. Any object or event in one place can have an influence on nearby areas. The influence is probably greater for nearby objects than for ones farther away. These basic principles are so important in geography that they are sometimes described as Tobler's First Law of Geography (Sui, 2004). Recent research, however, suggests that the human brain does not have any mechanism for encoding absolute location. On the contrary, mental representations of location are always relative, done "on the fly" for each object as we determine its position relative to other objects (Woodin and Allport, 1998; Mou and McNamara, 2002; Solstad, et al. 2004; Svoboda, et al. 2008). In fact, we construct mental representations using several different frames of reference, which in turn use different brain structures (Committeri, et al. 2004). The key idea in assessing spatial influence is the ability to recognize what is "near space" and "far space" for a specific purpose, such as touching, walking through a crowded room, throwing a ball, identifying the houses that are likely to have too much noise from an airport, or naming the cities that are within range of a missile in a particular location (Cutting, 1995; Hubbard and Ruppel, 2000; Kaya and Weber, 2003; Webb and Weber, 2003; Longo and Lourenco, 2006; Hund and Plumert, 2007). Ironically, some of the best research on the topic of spatial influence has been done by engineers trying to figure out how a robot can maneuver through a room without colliding with other stationary and moving objects. Unfortunately, much of this robot research is difficult to find, because it is being done in military

or private labs (a recent general summary can be found in Zender et al. 2008).

Our lessons for the Harlem school included a set that explored the concepts of near and far. Specific activities included making verbal descriptions of relationships among people, like "Keisha is closer to me than Carlos is." Other activities included a game that required the use of the words next to, near, close to, and far from. Then, while the students were making a model of their classroom, we encouraged the teachers to ask questions about the distances between various objects. We also urged teachers to take every opportunity to link these mapping activities with what students were doing in both language arts and mathematics lessons.

3. **Spatial groups (regions)**. A geographic region is a group of places that are similar to each other in some way and also close together (James, 1952). If we mark these places on a map, it is possible to draw a line around them, color the resulting area, and refer to that area by its regional name. For example, one might make a map with dots showing the locations of tall trees, draw a line around that area, and call the result a forest (this is "bottom-up" regionalization; see Ashby and Maddox, 1993). Similar logic can lead to the identification of regions based on many different criteria, such as suburban growth, new soybean fields, or abandoned fishing villages. Grouping places into regions is a valuable way to reduce the tremendous memory demands of trying to remember every individual tree, soybean field, and shopping center in the world (Duffy, et al. 2006). At the same time, however, the process of grouping can introduce distortions in spatial memory (Enns and Girgus, 1985; Kerkman, et al. 2003; Friedman, 2009).

The process of visual grouping of features on maps or satellite images has interested scholars from a number of different disciplines, including developmental psychology, vision science, remote sensing, and architecture, as well as geography (Goldstone, 1994; Stewart and Brown, 2005; Hampton, et al 2005; Kubovy, et al. 1998; Kim and Cave, 1999; James, 1952; Bunch and Lloyd, 2000). In the human brain, this process usually involves a chain of structures that extends forward from in the primary visual cortex near the back the head (Reber, et al. 1998; Haxby, et al. 2001; Weber, et al 2009).

Our spatial-region lessons for the Harlem school started with attempts to divide the classroom into regions with similar features – desk areas, play areas, reading areas, and so forth. Later in the year, the students went on a walking trip through the neighborhood. On that trip, they visited and described several places, including a mosque, clothing store, church, restaurant, and music theater. Several days later, the students were asked to draw pictures of the scenes they had seen on the trip. The next step in the lesson was to put the pictures into groups – places where people live, places where people shop, places where people worship, places where people go to have fun, and other places. This process of categorization has great value in language arts, in refining vocabulary and making decisions about appropriate words. It also provides a foundation for interpreting maps of vegetation, land use, and other geographic phenomena in later grades. We encouraged teachers to start that process of image interpretation in first grade, with a lesson that involves trying to draw lines around areas like Marcus Garvey Park and the Martin Luther King housing project on satellite image of the area near the school.

4. **Spatial transitions** (slopes, gradients, sequences). One way to begin a lesson about spatial transitions is to ask students if they know of a place where it is hard to walk or pull a wagon because the land goes uphill. If students can observe a change in elevation and describe its consequences, they have begun to make a fairly important kind of comparison, one based on elevation. Further development of this skill eventually will help them read trend-line graphs, terrain profiles, and isoline maps in later grades.

In order to describe a spatial transition, a person must be able to hold information about at least three locations in memory, *in their proper sequence*. That, in turn, appears to involve a specific area of the brain above the left eye (remember Phineas Gage? see Romine and Reynolds, 2004; Histed and Miller, 2006). The mental process actually relies on a network of several different brain areas (Ghaem, et al. 1997; Schendan, et al. 2003; Ross, et al. 2009). Furthermore, the mental activity appears to be the same for temporal or spatial sequences (Chiba, et al. 1997; Shin and Ivry, 2003; Botvinick and Watanabe, 2007). Interestingly, there is evidence that the mental representation of both temporal and spatial sequences is actually spatially arranged in the brain (Beiser and Houk, 1998; Gevers, et al. 2003). The nature of the path between places has an influence on the durability of memory (Stadler, 1992; Parmentier, et al. 2005). Finally (and of great importance for people interested in effective education), enhanced ability to process spatial sequences is an essential component both reading and mathematics (Vinckier, et al, 2007; Troiani, et al. 2009). After all, letters in a word, and words in a sentence, and sentences in a paragraph are all arranged in spatial sequences!

For our Harlem school, we made several lessons that addressed the concept of spatial sequences and transitions at different scales. The purpose of one lesson, for example, was to emphasize the meaning of the word "between." In this lesson, a teacher might ask students to describe the relative position of three colored dishes on a table – "the blue plate is in the middle" or "the red plate is between the blue and green plates." A teacher suggested this lesson because primary-school books in the United States often use color activities to reinforce writing skills; this teacher simply thought that she could also make the activity into a geography project by including spatial position in the description (Figure 2).

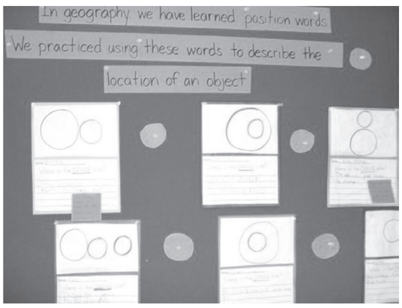

Figure 2: A bulletin board display shows samples of student writing with "position words".

Later, a teacher could ask students to put a clock symbol into the classroom model "where it really is in the classroom," between the two windows on the wall. The next logical question involves spacing – "Is the clock closer to the left window or the right one?" Later, the students were asked to name the rooms along the hallway in proper order, and label them on a blank school map that we provided. Still later, the students had to remember the landmarks on their field trip in proper sequence. Students in one class even decided to build a model of their field trip in the classroom, using desks to represent buildings and symbols like a green ball to represent the green dome of the mosque.

All of these sequencing activities are building a foundation for a variety of middle-school geography activities. For example, the rainfall pattern of Africa can be described as a sequence of places that have shorter and shorter rainy seasons as you go north, away from the equator. Neuroscientists, however, might add that we are not just building a vocabulary about spatial sequencing, we are actually helping students construct the brain connections that support that kind of spatial analysis.

5. **Spatial hierarchies**. A spatial hierarchy is a set of smaller areas that are inside of a larger area (or less important features that are subordinate to a more important one). A political map provides an easy-to-understand example. For example, Salvador is a city inside the state of Bahia; Bahia is one of 26 states inside the country of Brazil; and Brazil is one of 11 countries and one province inside the continent of South America. Other spatial hierarchies include watersheds, central place networks, and the administrative structures of organizations like a school system or the Roman Catholic Church.

Like regions, spatial sequences, spatial auras, and spatial comparisons, a spatial hierarchy is a mental device to help simplify our perception of the world. Hierarchical descriptions seem to involve structures on the right side of the brain; their effects is to reduce the amount of factual memorization required to remember a landscape or a map (Hirtle and Jonides, 1985; Holding, 1994; Hommel, Gehrke and Knuf, 2000). Our primary goal in designing educational materials, therefore, is to provide a useful set of anchor points, so that students can build their mental hierarchies around important landmarks, cities, and countries. A solid mental hierarchy, in turn, can prove useful in reading newspapers, watching television, and searching the internet in the future.

One of our first recommended geography activities in the Harlem school was to ask each student describe all of his or her "insides." Figure 3 is an example of the kind of "teacher guides" that we provided to guide discussion about each lesson.

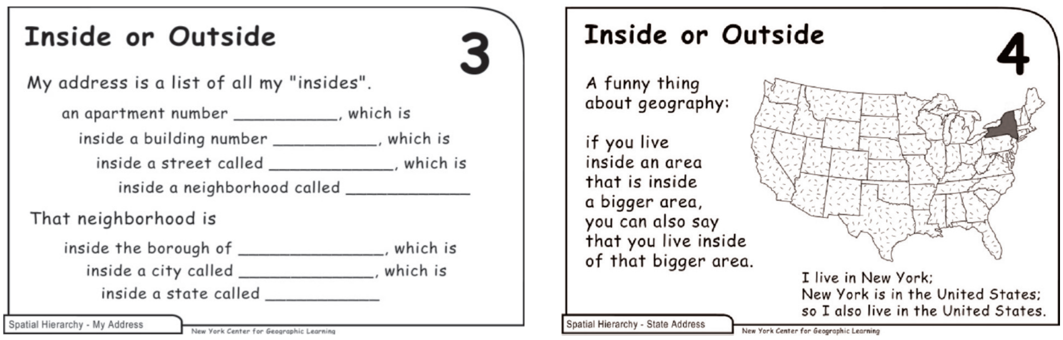

Figure 3: Each of our spatial-thinking lessons had a number of "teacher guides" like this.

As noted earlier, teachers then developed their own strategies for approaching the topic. To extend the "insides" activity, we provided sets of desktop maps that showed Harlem's location inside the island of Manhattan. Other maps showed Manhattan inside of New York City, NYC inside of New York state, and New York state inside the United States. At the same time, teachers were encouraged to use hierarchical terms in commenting on students' maps of the classroom, school, playground, and neighborhood. A "treasure hunt" activity involved hiding a treasure inside of a box and then describing the location of the box in the classroom. Students were encouraged to use words that described spatial groups, sequences, and comparisons as well as hierarchical terms, in order to promote cross-connections among different brain regions involved in different modes of spatial thinking. All of this is helping to build both a vocabulary (words like inside, outside, part of) and a set of neural connections that can later help students interpret traditional maps of watersheds, ecosystems, or urban forms (Plumert, et al. 1995; Kostylev and Erlandsson, 2001; Wang and Brockmole, 2003; Westaway, 1974; Wu and David, 2002).

6. **Spatial analogies**. A spatial analogy is a statement about two places that have similar positions on different continents (or in different cities, watersheds, countries, and so forth). For example, consider the central part of Chile, south of Santiago. This mid-latitude position on the west side of South America is similar to the location of the Napa Valley in central California, the Loire Valley of southern France, or the area around Adelaide in southern Australia. We should not be surprised, given their similar climates, that these four places all have international reputations as producers of similar products, especially wine.

Psychologists have long noted that analogical reasoning is one of the most complex kinds of human thinking (Sternberg, 1977; Keane and Bradyshaw, 1988; Gentner and Markman, 1997; Hummel and Holyoak, 1997). Brain scanning reinforces that idea, because analogical reasoning appears to involve a number of brain structures, including, especially, an area of prefrontal cortex near the top of the head (Waltz, et al. 2000; Green et al. 2004; Bunge, et al. 2005; Bar, 2007). Analyzing the implications for geography is complicated by a simple fact: a map is actually a kind of spatial analogy, because symbols on a page are deliberately put "in similar positions" as objects in the real world (DeLoache, 1989; Loewenstein and Gentner, 2001; Schmidt and Lee, 2006). The importance of similarity of position, however, extends beyond mapping. In fact, reasoning by analogy is a key component in promoting durable memories about spatial relationships (Endo and Takeda, 2005; Schmidt and Lee, 2006).

Several of the geography activities in our Harlem school had their primary focus on the idea of spatial analogies. Like the colored-dish activity that one teacher suggested to introduce the idea of spatial sequences, some of the first spatial-analogy activities involved books, dolls, and other familiar objects. In one activity, for example, a teacher made a game out of asking students to "put your book in the same position on your desk as my book is on my desk." Then, the students turned a large box into a classroom model and put objects such as windows, doors, and globes "in the same position in the model as in the real object is in the real room." This kind of activity builds the vocabulary, reasoning skill, and neural networks that students can then use in later grades to note that, for example, "Tashkent is an Asian city that is in the same location as Salt Lake

City in the United States; both cities are located between some mountains to the east and a desert to the west, with a large salty lake in it." That kind of analogical reasoning links a variety of places together and makes them all much easier to remember.

7. **Spatial Patterns**. The human brain has been described as a "pattern-seeking machine." We subconsciously try to see patterns in any arrangement of events or features; indeed, we often "see" patterns that are not there! (Whitson and Galinsky, 2008). Pattern recognition on a map or other visual display occurs near the back of the brain, behind the regionalizing area and close to the primary visual cortex (Wenderoth, 1995; Gilbert, Kesner and DeCoteau, 1998; Faillenot, Deceny and Jeannerod, 1999; Scheessele and Pizlo, 2007; Finkbeiner and Palermo, 2008). This arrangement has relevance when students learn to read, because letters must be identified as patterns of lines and arcs before they can be grouped into syllables (Dehaene, 2009). In fact, some of the most interesting research has started by comparing how children learn to read with different alphabets, which trigger different parts of the pattern-recognition system (Tan, et al. 2001; Thuy, et al. 2004).

   A substantial body of research suggests that large and small patterns are processed in different parts of the human brain (Martinez, et al. 1997; Postma, et al. 2006; Nucci and Wagemans, 2007). When we were designing lessons about spatial patterns for the Harlem school, we asked teachers to pay special attention to the distinction between different kinds of patterns:

   whole-area patterns (tendencies for objects to be located mainly on one side, in a corner, or in the middle of a space such as a room or a sheet of paper), and

   small-area patterns (pairs, alignments, rings, waves, and other small details).

   In essence, learning about spatial patterns is basically a process of learning the visual impressions that are customarily described by pattern words such as line, arc, ring, and, later, centripetal, wavelike, subparallel, en echelon, etc. Learning a sophisticated pattern-description vocabulary does not happen all at once – it takes time and goes through some recognizable developmental stages (Tada and Stiles, 1996). Our primary-school lessons, therefore, are designed to build a foundation for middle-school lessons that ask students to describe and analyze the spatial patterns of real-world phenomena such as earthquakes, malls, or settlements on the West Bank of Israel. We should note, however, that geographers rarely think that the analysis of spatial patterns is an end in itself. On the contrary, it usually serves as a prelude to the last of our modes of spatial reasoning, the analysis of spatial associations.

8. **Spatial associations (correlations)**. A spatial association is a tendency for two things to occur together, in the same places (and therefore to have similar patterns on a map). The practical significance of thinking about spatial associations becomes apparent when we make a list of some famous spatial associations. For example, rich fishing grounds are spatially associated with areas of cold-water upwelling; malaria has a map pattern that is similar to that of Anopheles mosquitoes; successful businesses are often located in communities with particular demographic traits; urban crime rates are related to some kinds of public investments; and so forth (Dangendorff, et al 2002; DeMotto and Davies, 2006).

Because spatial correlations have obvious value in trying to understand causal relationships, applied geographers have been developing ever-more-sophisticated ways to analyze spatial associations for more than half a century (Robinson and Bryson, 1957).

Like the other seven modes of spatial reasoning, the mental analysis of spatial associations makes use of a distinctive network of structures in the human brain, with a prominent peak of activity in the perihippocampal area (Arminoff, Gronau and Bar, 2007; Chua, et al. 2007; Bachevalier and Nemanic, 2008). Moreover, as with all of the other modes of spatial thinking, there appear to be significant individual differences among students when we try to measure their ability to observe and remember spatial associations. Individual differences in performance on tests that use different kinds of spatial thinking, however, are not well correlated – in fact, students who are proficient with one kind of spatial thinking, such as spatial association, are often less able to do other kinds of spatial reasoning, and vice versa. In general, females tend to score better on tests that involve spatial associations, whereas males seem to do better with tasks that involve spatial sequencing or mental rotation (McBurney, et al. 1997). These differences, however, are complex and subject to many influences, such as age or social class (Levine et al 2005). Evidence suggests that all students can become more proficient in all forms of spatial reasoning, but some scholars have recently suggested that improvements in some modes may limit the rate of improvement of others (Woollett and Maguire, 2009).

These debates are too recent and too complex to be resolved in this review. After all, it has been barely a dozen years since people thought that spatial thinking was a single kind of "intelligence." We suspect that future research will uncover more intricate connections among various modes of thinking. We therefore will end this research review by noting that our suggested lessons for the Harlem school included several activities that encouraged a search for spatial associations. In one, students were asked to make lists of "things that are usually found together in the same room, like toothbrushes and toothpaste, or books and comfortable chairs." In another activity, often presented as part of their efforts to make a map of their classroom, we asked students to try to name things that go together in the same part of the room, like desks and chairs. Observing spatial associations like this proved to be a difficult task, and therefore it is especially important to start the process in early grades, when students are beginning to acquire the basic tools of spatial analysis.

Discussion

In this paper, we briefly summarized an ongoing review of a huge amount of recent research in the neuroscience of spatial cognition (we have examined more than 3200 studies published since 1995). Based on that review, we have described eight distinct modes of spatial reasoning. These modes of spatial thinking are essentially different ways of organizing spatial information; the new research suggests that they actually use different structures in the human brain. This list of modes, in turn, became the basis for a set of lesson ideas that we presented to the teachers in nine kindergarten and first-grade classrooms in the low-income Harlem neighborhood of New York City.

For reasons explained earlier, it is still too early to try making a rigorous comparison of the effectiveness of these lessons. That kind of comparison is extraordinarily difficult even in a well-established school system. It is all but impossible in a new school, with a new curriculum, in a low-income neighborhood with high rates of student and staff turnover.

We do, however, have a set of numbers that show the performance of these students on the standardized tests that are required every year in the New York City school system. Test scores by the students in the nine Harlem classrooms went up dramatically through the school year. Most of the room averages were in the mid-50s in September and the low 90s in May. For comparison, the city average on one of these tests was 47.

Scientific integrity does not allow us to make any assertions about cause and effect. We cannot "prove" that the geography lessons led to higher reading and math scores. We will therefore conclude by noting (albeit with some pride) that we have obeyed the Hippocratic Oath of the medical profession – "first of all, do no harm." We repeat – we cannot say that our geography lessons will improve scores on reading and math tests. We can say, however, that carefully-designed geography lessons that focus on spatial thinking did not seem to cause harm – they did not lead to lower reading and math scores, even though they did take a significant amount of time away from reading and math instruction. Similar results have been observed in a few studies in other states (Dorn, et al. 2004). In this review, we do not have space to explore this important issue in detail. Suffice it to say that this conclusion is supported by a large number of ideas that emerge from recent neuroscience research (for a representative sample of this work, see Fischer, 2003; Helland and Asbjornsen, 2003; Carreiras, et al. 2007; Vinckier, et al. 2007; deHevia and Spelke, 2009; van Dijck, et al. 2009 and, especially, Dehaene, 2009 and Pasnak, et al. 2009)

We have two other kinds of "evidence" that may be relevant to any discussion of school curriculum. When students in the Harlem school were asked to name their favorite subjects, geography was one of the top two subjects on nearly every student's list. And when the school administrators decided that geography was motivationally important, they suggested that it might be desirable to hire a geography specialist to teach the geography classes (like they have specialists to teach their science and art classes). The response of the other classroom teachers was a unanimous vote – they did not want to give up their geography classes. We infer that those teachers saw the value of our geography lessons in helping to connect other school subjects and make school seem more worthwhile.

Conclusions

Spatial thinking is an important part of human cognition (Downs and deSouza, 2006). New brain-scanning technologies suggest that spatial thinking is not a single kind of "intelligence." On the contrary, it appears to be a complex set of parallel processes that involve a number of specialized structures in different parts of the human brain (Burgess, 2008). In this paper, we have tried to provide a concise but thorough summary of research in a number of academic disciplines, including neuroscience, behavioral psychology, linguistics, architecture, and robot engineering. Our primary purpose was to identify research that is relevant for people trying to design instructional materials in geography and social studies. With that in mind, we illustrated our review by describing some geography materials that we designed for a new school in New York City. We are planning to conduct a more rigorous test of effectiveness of those materials in the future. In the meantime, we hope that our careful review of research in other disciplines might help people who are trying to improve geography instruction in other schools around the world.

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