Spatial Thinking by Young Children: Neurologic Evidence for Early Development and "Educability"

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ABSTRACT

The human brain appears to have several "regions" that are structured to do different kinds of spatial thinking, according to a large and rapidly growing body of research in a number of disciplines. Building on a previous review of research with older children and adults, this article summarizes the research on spatial thinking by young children. Three conclusions: brain structures for spatial reasoning are fully functional at a very early age, adult intervention can enhance both use and representational ability, and practice in early grades is an important, perhaps even essential, part of the scaffold for later learning.

Key Words: *spatial thinking, brain, cognition, neuroscience, scaffold*

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INTRODUCTION

People involved in geographic education must never lose sight of a simple fact: children are not just miniature adults.

Children have less background information than adults do, which makes it harder for children to decide whether something they encounter is "normal" or "extraordinary." They have smaller vocabularies, which makes it more difficult for them to express complex or subtle ideas. Their muscles and joints are exceptionally flexible, but they have not had enough time to practice controlling their movements. Even their brains are still developing.

The last point may be the most important for educators, although the first three are also significant in many educational settings. A child's brain is still making new cells and neural connections (Nelson *et al.* 2000). This observation is the neurologic foundation for a number of theories about developmental stages and readiness for certain kinds of learning activities. Many, but not all, of those theories are based on the pioneering work of Piaget and Inhelder (1956), which helped trigger half a century of research about spatial thinking by young children. In the last fifteen years the pace of research has accelerated, aided by the invention of new technologies for brain scanning. As geographers, we are particularly interested in what psychologists now know about the development of brain structures and connections that help people do what the National Research Council (2006) calls "spatial thinking at geographical scales"—thinking about locations, characteristics of places, and relationships among places.

The purpose of this article is to summarize that research and to apply it to the question of developmental readiness for particular kinds of geography lessons. Specifically, we will examine the psychological research that deals with eight distinct modes of spatial thinking[1] that have been described in recent reviews of research about adult spatial cognition (Golledge and Stimson 1997; National Research Council 2006; Gersmehl and Gersmehl 2006). Our goal in this article is to explore the available research in order to determine which of those spatial-thinking skills appear to be within the neurologic competence of young children and therefore should be taught in primary school.

In short, we are trying to summarize what brain scientists and developmental psychologists would say if we asked them a simple two-part question: what kinds of spatial thinking can young children do, and at what age can they start?

LOCATION: WHAT MAKES A TOPIC GEOGRAPHIC?

The concept of location seems simple enough, until you try to describe a location without invoking at least one other spatial concept, such as distance, direction, proximity, enclosure, or topology. At that point, you begin to realize that humans have developed a surprisingly large number of distinct, often subtle, and occasionally complex ways of describing location. This diversity occurs partly because the research verdict is in: the human brain does *not* have a mechanism for storing and retrieving information about so-called "absolute" locations. "The concept of location is inherently relative" (McNamara 2003; see also Pani and Dupree 1994; Huttenlocher *et al.* 1999; Mou and McNamara 2002).

How does the human brain store locational information? Apparently it uses an interconnected system of at least three different brain areas that separately encode relative locations according to different frames of reference (Committeri *et al.* 2004; Hartley *et al.* 2004; and more than sixty other studies). One of those frames of reference is based on the geometric characteristics of everyday objects. For example, when people talk about "the front row of seats" or "the left aisle"

of a movie theater, they are using a frame of reference that is established by the direction a theater seems to "face" its most important feature, namely the screen. When a person turns into a row and starts looking for a particular seat, however, a bystander might offer some advice: "keep going; seat C14 is about ten feet in front of you." That advice uses a different frame of reference that is set by the body orientation of the person trying to find the seat.

The "front door" of the theater, on the other hand, implies a third frame of reference that is set with respect to the surrounding environment, usually the street that goes by. Indeed, the "front door" of a theater is often located near what someone inside the theater would call the "back" of the theater! Things get even more complicated when we are talking about multiple theaters in a mall complex, or when advice-givers choose not to use the viewpoint of people to whom they are talking, and therefore might say something like "seat C14 is over there, to my left."

The idea of location is basically relative, and it can be communicated in many ways (Fig. 1). These "languages" of communication occasionally use the same words to mean different locations and relationships, depending on whether the frame of reference is based on the speaker, the hearer, the object, the surrounding environment, or a distant and arbitrarily defined feature such as the prime meridian (Landau 1996). Child psychology books of the late twentieth century often linked these frames of reference with developmental stages, using words such as "egocentric" or "preoperational" to imply that young children first view the world only in relation to their own bodies. Later (according to this theory), they learn to use other frames of reference. Recent studies, however, seem to point to a different conclusion: "children as young as 3 years therefore had, and greatly favored, spatial representations that were not purely egocentric . . . [we conclude that] core components of adult spatial competence, including parallel egocentric and nonegocentric representations of space, are present as early as 3 years" (Nardini *et al.* 2006; see also Bluestein and Acredolo 1979; Hale *et al.* 1997; Rutland *et al.* 1993; Bell 1999; Dalke 1998; DeLoache *et al.* 1999; Huttenlocher *et al.* 1999; Blaut *et al.* 2003; Vasilyeva and Huttenlocher 2004).

Describing a Location
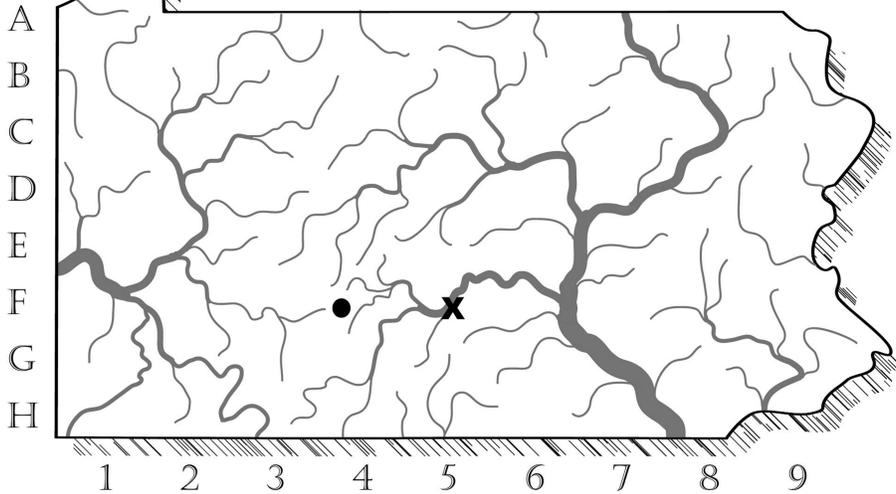
How would you describe the location of the dot?

Landmark: next to the building at the top of the inclined plane.

Proximity: close to (2 miles south of) the railroad tunnel in Gallitzin.

Topology: halfway between Ebensburg and Hollidaysburg on US22.

Hydrology: at the source of Blair Gap Run, near the drainage divide (between the Connemaugh and Juniata river systems).

Elevation: 748m above sea level, in Blair Gap in Allegheny Ridge.

Ownership: in Allegheny Portage Railroad National Historic Site.

Enclosure: just inside the east border of Cambria County.

Hierarchy: in Cresson town, in Cambria County, in Pennsylvania. (or Blair Gap Run, Juniata River, Susquehanna River, Atlantic Ocean)

Polar coordinates: 50 degrees and 28 km from Johnstown airport.

Latitude/Longitude: 40°27' N and 78°33' W.

Map coordinates: in (the western part of) map grid cell F4.

Map position: about an inch to the left of the X on the Juniata River.

General scaling: about 1/3 of the way in from the left side and 1/3 of the way up from the bottom of the box called Pennsylvania

Then there are UTM coordinates, the state plane grid, road mile markers, geologic provinces, soil mapping units, state game land designations, stream reach numbers, view triangulation, historic ownership, Post Office addresses, Emergency Management Agency codes, etc. etc.

Figure 1. Different ways of describing the location of a historically important place.

Based in part on these recent research studies, the authors of this article are now helping teachers experiment with a number of teaching ideas in a multiclassroom K-1 school in Harlem, New York, and an integrated K-12 school in Queens, New York. These teachers are introducing alternative frames of reference with modified versions of Put Me on the Map, Simon Says, the Telephone Game, Find the Bear, and the Story Word Wall (Leather 2006). These preliminary "experiments" are taking place in the first year of collaboration between these schools and the New York Center for Geographic Learning, and therefore we cannot draw any firm conclusions at this time. All we can say is that the behavior we have noted in more than twenty hours of classroom observation in autumn of 2006 is consistent with the main conclusion of the previous research: kindergarten children can and do use multiple frames of reference. Indeed, the major pedagogical challenge appears to be one of extension, not introduction: trying to get students to reflect on, and more finely tune, the frames of reference they are already using, and to represent their knowledge in different modes (e.g., verbally, with gestures, or by using a tabletop model or map of the classroom). The task (and it *is* a substantial one) consists of trying to refine the use of an existing multiple-frame concept of location, by clarifying the vocabularies of communication about position, rather than trying to learn new ways of looking at the world.

Conditions and Connections: The Basic Facts of Geography

For geographers, the facts about a location fall into two logically distinct but complementary groups, which work together like two hands clapping. One hand holds all the *conditions* that occur at a particular place—its climate, architecture, population density, vegetation, animals, agriculture, industry, politics, religion, and so forth. The other hand holds all the *connections* between a particular place and other places, near and far. Those connections can be "natural" (slope, wind, river flow, seed dispersal, animal migration, etc.) or human-induced (trade, commuting, corporate control, family ties, political authority, etc.)

This two-handed conception of location has been accepted among geographers for a long time. The specific terminology used to describe the two aspects of location, however, has changed several times. In the mid-1900s, for example, geographers often referred to the two facets of location as *site* and *situation*. That pair of words is reasonably accurate and easy to remember, but unfortunately they already have different meanings for historians, other social scientists, and nonacademics. As a result, geography teachers and textbooks that used these terms had to redefine them for geographic use, and that redefinition had to be repeated nearly every time the terms were used.

When a group of geographers got together in the 1980s to write what eventually became known as "The Five Themes of Geography," they first suggested that the two aspects of location should be described as "relationships within places" and "relationships between places." Those phrases were later shortened (and, in fact, repositioned within the list of themes) to become the single words "place" and "movement."

Regardless of what terms are used, the distinction between conditions and connections is important, partly because the human brain appears to acquire and store information about place (conditions) and movement (connections) in different modes. "These strategies [spatial thinking by associating landmarks and tracing routes] may be subserved by different cortical areas [in the brain]" (Aginsky *et al.* 1997, 317; see also Burwell *et al.* 2004; Ekstrom *et al.* 2003; Ferguson and Hegarty 1994; Golledge *et al.* 1995; Gouteux *et al.* 2001; Hartley *et al*. 2004; Newcombe *et al.* 1998).

The research clearly points to the conclusion that the process of linking the "where" facts of location with the "what" facts of conditions and connections is more complex and indirect than many people suspect. Moreover, in most cases, people acquire spatial knowledge by applying other modes of spatial thinking. This happens for a very good reason—the world is a huge and complicated place. It is simply not possible for the human brain to memorize all of the conditions and connections in every place around the world (Fig. 2). In fact, some researchers suggest that the other modes of spatial thinking exist primarily to help people organize and remember the facts that they deem important (DeLoache and Todd 1988; Gattis 2001). That conclusion, in turn, has significant implications for educators.

The picture gets even more complicated when you include variables such as gender, language, mobility, socioeconomic class, and even left- or right-handedness. For example, it is a well-established fact that male and female children usually perform differently on tests that measure recall of conditions at places and connections between places. In general, females do better with conditions, males with connections (for reviews of different parts of this extensive literature, see Lehnung *et al.* 2003; and Ecuyer-Dab and Robert 2004). What is not known is why these differences occur and what should be done about them. The answer, however, might lie in individual differences in the use of other modes of spatial thinking, notably about regions, hierarchies, sequences, and associations. For that reason, we will turn to the question that needs to be answered first: at what age can children begin to learn the various modes of spatial thinking that appear to be neurologically distinct in adults?

Spatial Thinking: Eight Neurologically Distinct Modes of Thinking about Conditions at Places and Connections among Places

This part of our article contains a brief description of eight distinct modes of spatial thinking. Each description

Facts About Places (and why you can't possibly learn them all)

	Total So Far
Stand in the middle of a room in your house.	
Write ten facts about what you see in front of you	10
A typical room has four walls. Multiply by 4 (or ? for complex rooms).	40
A typical house has 5 rooms. Multiply by 5.	200
Add facts about the outside and yard. Add 50.	250
A typical block has 20 houses. Multiply by 20.	5000
A community might have 50 blocks. Multiply by 50.	250,000
The U.S. has about 40,000 communities. Multiply.	1,000,000,000
The world has 20 times as many people as the US. (Many houses have fewer than 5 rooms. Divide by 2)	200,000,000,000 100,000,000,000

So far, we have looked only at houses. Add facts about all other features:
oceans, lakes, rivers, mountains, deserts, islands,
farm fields, barns, pastures, fences, windmills,
stores, factories, offices, churches, cemeteries,
restaurants, theaters, parks, airports, etc., etc.

at least 500,000,000,000

What's a good guess how many?
Multiply by 5? 10? 20?

P.S. I bet you can think of more than 10 facts about one view in a room!

We study geography in order to learn some skills that can help us try to organize and remember important facts out of this mass of information.

Figure 2. A brief math lesson to illustrate the futility of trying to learn facts about every place in the world.

includes a brief summary of research concerning the childhood development of that mode of spatial thinking (for a more thorough review of the neuroscientific foundations of those processes in adults, see Gersmehl and Gersmehl 2006). That brief summary is followed by some suggestions about how teachers in primary schools might help children use (and therefore improve) their skill in that particular form of spatial thinking.

Comparison

One mode of thinking about conditions and connections in "new" places is to compare them with places that are more familiar. The process of comparison appears to be an innate trait of human cognition. Persuasive evidence for that conclusion arises out of the fact that every human language has grammatical structures and categories of words that are specifically devoted to comparison. "Not only do children [from several different countries] show a grasp of a variety of spatial notions before they can talk about them, but they also seem to draw on this knowledge in learning new spatial words" (Bowerman 1996, 389; see also Goldstone 1994). Another study of preschool children concluded that comparison acts as a bridge toward other modes of spatial thinking: "the process of comparison, viewed as a process of structural alignment, constitutes an important route towards abstract conceptual understanding" (Gentner and Namy 1999, 589). Good teachers have known this for a long time. They have taught about comparisons in language arts (e.g., soft, softer, softest), mathematics (counting, measuring), and even art (visual perspective and other modes of implying unequal sizes at varying distances). Recent years have witnessed an upsurge in the use of graphical devices such as Venn diagrams to help children organize their thoughts as they compare photos, objects, stories, times, and places. This particular pedagogical device is especially interesting to geographers because it makes use of another modes of spatial thinking—regionalization (refer to Regions section). In effect, a Venn diagram is a device to help students arrange words in groups within visual space in order to remember them better. In short, there are a sizeable number of "strategies" for comparison, and if children begin learning to use them to compare places in kindergarten, they are likely to be better equipped to remember information about places and to learn about new places in later grades.

Aura

A spatial aura is a zone of influence around an object. Things like dead skunks, noisy machines, and bright lights have an obvious influence on nearby areas. The same principle applies to larger geographic features, such as rivers, airports, factories, parks, and missile bases. These features all have an observable influence that can have an effect on quality of life, property value, and occasionally even safety in the areas around them. As a result, the analysis of the extent and intensity of influence around objects is an important part of applied geography in later grades and in adult life (Eldridge and Jones 1991; Ferscha *et al.* 2004). What neuroscientists have learned in recent years, however, is that the "analysis" of spatial influence makes use of some specific structures in the brain. In effect, human beings (along with many other animals and even some plants) appear to be "hard-wired" to imagine an aura of influence around themselves and other objects. You can see this when two crowds of people surge toward each other from opposite sides of a street when

a traffic light changes. Somehow, people seem to avoid running into each other without spending too much time consciously thinking about their actual paths. In effect, our visual systems and brains subconsciously build a kind of imaginary shell or buffer zone around our bodies and all nearby people and objects. An alarm of some kind goes off in our heads when our subconscious "traffic monitor" notices a possible future intersection of auras (Cutting *et al.* 1995; Hubbard and Ruppel 2000). This particular kind of eye-brain activity sets us free to ignore other people (and even vehicles on a highway) unless their aura seems likely to intersect ours. In fact, the sheepish grins and awkward shuffles that occasionally occur when "the system breaks down" are a form of indirect evidence for how effective the "aura machine" in our heads usually is.

The process of "boundary extension" around objects and views has been described as "a fundamental component of spatial cognition" (Intraub 2004, 34; see also Moulin and Kettani 1999). This research seems to indicate that infants have a fairly well developed sense of their own personal zone of influence by the end of the first year, and that they soon begin to extend that awareness to other objects and living things. By age three, however, many children still find it easier to find objects that are described as "within a landmark, such as a box" rather than "next to the landmark" (Plumert and Hawkins 2001). Primary school teachers should be sensitive to the possibility of great individual differences in the awareness of a zone of influence around people and geographical features (e.g., Vranic 2002). Teachers can help build a foundation for later analysis during field trips or video presentations by discussing the idea of "nearness," pointing out some features that might have an influence on nearby objects, and then extending the idea to include discussion of different kinds of influence—smell, sound, smoke, and so on. Teachers in later grades can then build on that understanding as they design lessons that encourage students to see the effects of influence on maps. For example, a large city is likely to have an economic influence that encourages in-migration and higher population densities in nearby counties. If a person brings an awareness of the likelihood of influence to the map-reading task, that person should not be surprised to see a ring of counties with a medium density around the densely-populated core of virtually every major urban area on a choropleth map of population. In this way the awareness of a zone of influence around cities can help middle-school children remember important settlement patterns in the United States without trying to memorize the actual colors used to fill all 3,000 plus counties on a population map.

Region

A region is a group of adjacent locations that have similar conditions or connections. For example, the Corn Belt is a region where people grow corn. Bengal is a region where people speak Bengali. The Atlanta commutershed is the region where a sizeable fraction of people commute to work in Atlanta. The process of regionalization is basically a form of classification, with an explicitly spatial dimension—the mind searches for places that have something in common and are located adjacent (or at least close) to each other (DeLoache and Todd 1988; Gelman and Markman 1986; Wiener *et al.* 2004). Human visual systems do this all the time, as they rather effortlessly decide which colored patches on the retina of an eyeball belong to this tree as opposed to that car or the building behind them both (Gilbert *et al.* 1998). A well-designed geography lesson can help children do the same thing with drawings of the classroom and playground or aerial photographs of the neighborhood (Plester *et al.* 2002). That activity can, in turn, help build a foundation for future interpretation of satellite images and census maps. At the same time, children should gradually learn to appreciate that a "pre-made" regional map is a human invention, made by someone who has simplified the world by organizing large numbers of places into a small number of regions. In short, the goal of regionalization, as with other modes of spatial thinking, is to make information about places easier to remember and communicate.

The previous paragraph is rather short; because of all the modes of spatial thinking on this list, the making of regions has had by far the most discussion in geography classes and textbooks. Indeed, the process of regionalization is the only one of eight neurologically distinct modes of spatial thinking that is specifically represented in the five themes of geography. The use of regionalization as a tool for organizing knowledge is one of the key contributions of geography as a discipline, but it is not the only one: the main purpose of this article is to encourage teachers to add other forms of spatial thinking to their lists of skills to be taught. Based on our findings, the five themes were a good reflection of the neurological and pedagogical understandings of their day, but a large body of subsequent research strongly suggests that the process of spatial thinking is more complex, which in turn may justify a revision of geography's pedagogical goals.

There are two reasons to undertake this revision. First, a focus on a broader list of spatial-thinking skills would give teachers better tools to accommodate the very real possibility of more complex individual differences in the way children learn and organize information about places. Second, there are topics within geography that have traditionally been taught through the lens of regionalization but actually may be better communicated by invoking another mode of spatial thinking. For example, the world pattern of climate may be more effectively taught by asking children to think about spatial hierarchies, transitions, or analogies (as explained in Hierarchy; see also Gersmehl and Kammrath 1979, for an example of a transition-based alternative to the standard Koeppen-like textbook maps of climate regions).

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Hierarchy

A spatial hierarchy consists of nested areas of different sizes. This concept is easy to illustrate with political areas. A state, for example, is part of a larger country, and at the same time it has smaller counties within it (and those counties may have cities within them, and neighborhoods within cities, and so on). The idea of a spatial hierarchy, however, can also be applied to watersheds, wholesale distribution areas, professional baseball "farm teams," and many other topics in both physical and human geography. In recent years, neuroscientists have gathered a great deal of evidence that human beings organize space by creating a general framework of important places, which allows the addition of information at more detailed scales to specific parts of the area without requiring revision of the basic framework (Holding 1994; Hommel *et al.* 2000).

This process of organizing spaces into hierarchies begins at a very early age. The efficiency of that process, however, appears to be hindered in very young children by the tendency for spatial working memory to become overloaded with too much unorganized information (Sandberg 1999; see also Liben and Yekel 1996). For this reason, teachers should be very careful to send a clear message that some geographic features are more important than others and therefore more worth memorizing. In other words, teachers should try to guide students to anchor their hierarchies on places that are intrinsically more important in understanding other patterns of environment, population, and economy. In primary grades, teachers often use devices such as rugs and desk arrangements to create spatial hierarchies within the room. Concepts of direction can be introduced by consistently labeling key features in the school, such as classroom walls, with direction terms that can then be extended to situate the classroom within the outside world. In the local community, teachers can help students build a mental hierarchy by choosing a limited number of important landmarks and trying to be consistent in describing other locations with respect to them. Later, in middle school, that concern for helping students develop an efficient spatial hierarchy for organizing future knowledge might result in curricular change, with less emphasis on scattered facts about Machu Picchu, Lapp reindeer herders, Tibetan monasteries, the statues of Easter Island, and other remote places. No one is trying to deny that those places are interesting and worth knowing about, but taken as a group they do not add up to the kind of spatial hierarchy that can help students see how their lives are affected by Pacific ocean currents, Nigerian oil wells, Indonesian clothing factories, or the Amazon rainforest.

Transition

A spatial transition is a change from one place to another. Any bicycle rider can tell you that the slope of the land (the change in elevation) between two places can be every bit as important as the actual elevation in either place (a condition of that place). Recent neuroscientific studies appear to support a theory that the human brain stores information about environmental gradients as a parallel and independent mode of processing spatial information (Jacobs and Schenk 2003; see also Smith and Sera 1992; Histed and Miller 2006). Asking young children to remember and describe things they observe on their route to school can help them develop their spatial sequencing ability. A logical next step is to have them arrange pictures of prominent landmarks into proper order. Teachers can begin with landmarks along a walking trip in the local community, then show pictures of major scenes elsewhere in the community, then in the home state, and finally from major regions on other continents (e.g., pictures taken at different latitudes from equator to pole). At the same time, young students can begin to develop their number sense by trying to record the change in some countable feature, such as the width of lawns along a suburban street or the number of floors (rows of windows) on buildings along an urban street. As they enter middle school, students can extend their math skills by learning some of the graphic methods that people could use to help visualize transitions from place to place. These graphs can be used to display information about a variety of gradients, such as elevation, rainfall, population density, family income, house age, crop yield, Republican vote, etc, (for a review of the neurological underpinnings of this graphical-visualization process, see Tversky 2001).

Analogy

Spatial analogs are places that may be far apart but have locations that are similar, and therefore they may have other conditions and/or connections that also are similar. For example, Los Angeles and Casablanca are on different continents, but they are about the same distance north of the equator. Both are located near the west coast of their respective continents. Both occupy a similar position on low hills between the ocean and some coastal mountains. As a result, both cities have hot, dry summers and mild, occasionally rainy winters. These conditions allow people near both cities to grow olives, oranges, and other specialty tree crops. Moreover, both areas face the same seasonal threats: smog in summer, wildfires in early autumn, and mudslides in winter. People who know a little bit about Los Angeles can communicate quite a bit of information by simply stating that Casablanca is "like" (i.e., climatically analogous to) Los Angeles. In a similar way, people can describe inner-ring suburbs in different cities as urban settlement analogs, because they have similar situations with respect to their central cities. As a result, they often have similar road networks and patterns of housing, retail trade, and population.

Reasoning by analogy is a powerful method for organizing impressions and hypotheses about the world, and it begins to develop very early in childhood. In one classic study, very young children often performed better

than adults when they were asked to point to spatially analogous locations on photographs. In the words of that researcher, children were good at answering questions like "if this tree had a knee, where would it be?" (Gentner 1977, 1037). Many other researchers have concluded that "children as young as 3 years of age have the underlying competence" to transfer inferences and form analogies (Brown *et al.* 1986, 103; see also Holyoak and Thagard 1997; Loewenstein and Gentner 2001). Moreover, "explicit training of the less proficient reasoners [among a group of 4-year-olds faced with an analogic problem] had a significant, positive effect on performance" (Alexander *et al.* 1989, 65). For example, if classrooms in a school typically have one wall of windows, students can be encouraged to recognize that the window walls in different classrooms are likely to have some features in common. For example, they have more light, which makes them a preferred location for plants. At the same time, the presence of windows can pose difficulties for hanging maps or placing tall bookcases, and so forth. Students can also look for analogous areas in different homes by describing what kinds of furniture typically go in kitchens, bathrooms, bedrooms, etc. Later, the same logic can be extended to help describe neighborhoods within cities or fields within farms. Designing lessons that encourage students to use spatial analogies to organize their mental maps of the world can be an effective way of making use of (and thereby improving) this mode of spatial thinking.

Pattern

A spatial pattern is an arrangement of things that is not random—an imbalance, alignment, cluster, wave, string, ring, etc. that can be seen and described. The ability to see patterns depends in part on prior knowledge of forces that might bias a spatial pattern away from random. For this reason, it is not surprising to see that the skill of spatial pattern analysis begins in infancy but continues to develop throughout childhood and even into adulthood (Burack *et al.* 2000). In an elegant experiment, Tada and Stiles (1996) presented a large number of children of varying ages with the task of reproducing simple geometric figures such as squares and lines that crossed at different angles. The results of this experiment clearly show how important it is to make a distinction between cognition and representation. Children as young as three could recognize when adults deliberately made errors in copying patterns. Few children below the age of four or five, however, could accurately place sticks to duplicate a pattern themselves. Moreover, they could not copy the pattern with a crayon or pencil on a blank piece of paper until age five, six, and sometimes even seven (depending on the complexity of the pattern). Children could show that they recognize a spatial pattern at quite an early age, but many could not muster the hand-eye coordination to reproduce the pattern until several years later. Uttal and others (2001) extended this study to show that direct instruction about the existence of

an underlying figure (e.g., a dog) in a pattern of dots helped children of age five to search for a "hidden treasure" more efficiently. These results indicate that children can grasp the idea of spatial pattern at an early age. The efficiency of pattern analysis in adulthood, however, depends in part on how frequently and successfully people have looked for patterns in the past. This is because one good way to tell someone about a pattern is to compare it with a familiar one, perhaps by saying something like "the houses in that neighborhood are not as close together as the ones along 84th street where you live." Eventually, students should develop the ability to make international comparisons, like "the pattern of villages in this area is biased toward the west, but not as dramatically as the pattern of Palestinian settlements in the West Bank area." To help build a foundation for that kind of comparative pattern analysis in later grades, a primary-school teacher in an urban area can arrange small wooden or plastic blocks in different patterns on a table (rows, circles, etc.) and ask which arrangement is the best representation of the buildings in their neighborhood or the shrubs in a lawn. As with any form of cognition, practice that helps build prior knowledge of spatial patterns can improve the ability to learn new forms of pattern analysis, which is an argument for introducing lessons on map pattern analysis fairly early in the curriculum.

Association

A spatial association is a pair of features that tend to occur together in the same locations, like squirrels and oak trees or coral reefs and tropical islands. At first, children must be encouraged to notice when they encounter the same pairs of features occurring together in different places (see Hund *et al.* 2002; Cornell *et al.* 1989; Blumberg*et al.* 2005). Research has shown that three-year-old children can find buried objects after being told about their association with particular landscape features, and four-year-olds can use other spatial cues to distinguish between simple one-to-one feature associations and ones that also depend on noting relative location within a group of similar features (Blades and Cooke 1994). At a very early age, children can be taught to notice "usually-next-to" associations of features on photos or maps. Moreover, the use of small models to make "maps" of feature associations such as traffic lights at street intersections or newspaper boxes near subway stops can help young children develop their ideas of spatial representation. In the Harlem and Queens schools previously mentioned, the teachers encourage kindergarten and first grade children to make verbal statements about associations of objects (e.g., "clocks are between windows" or "the greenboard in each classroom is on the wall near the door"); these statements, in turn, help them learn how to make better models and maps of their classroom. In later grades, children can then learn how to apply the skill of spatial pattern comparison in order to uncover spatial associations that might have causal

significance, such as the association of insects and human diseases in equatorial countries. For example, in Africa the areas of endemic malaria coincide almost exactly with the areas that have *Anopheles* mosquitoes—that observation helped narrow the list of possible suspects and eventually led to clinical tests that verified the mosquito as one of the chief vectors of the disease.

CONCLUSIONS

The human brain has some extraordinarily complex structures for the storage, retrieval, and analysis of information about objects, places, and times. In recent years, neuroscientists have learned how to observe relatively small areas of the brain in order to figure out what kinds of "thinking" appear to be done in those areas. Those brain-scanning technologies, in turn, have led many to the conclusion that the brain has some distinct regions that are structured to perform particular kinds of thinking (as well as some areas that apparently can be reassigned to assist with different kinds of thinking at different times). Several of the most specialized regions appear to be devoted to doing specific kinds of thinking about locations and spatial relationships, that is, associating features with locations, grouping similar places into regions, organizing features into sequences between places, seeking analogous geographic situations, and so forth. One byproduct of these discoveries has been a number of articles that call for a revision of earlier concepts about brain function (e.g., Kozhevnikov *et al.* 2002)

Parallel research by child psychologists and educational specialists tends to reinforce one main conclusion of the neuroscientists: the brain areas that are devoted to different kinds of spatial thinking seem to develop in very early childhood. This conclusion is opposed to what you may have read in your college child-psychology book. As one researcher whose focus is on the linguistic aspects of spatial thinking said:

> . . . the idea that very young children might possess such rich and flexible representations of objects is at odds with traditional theories of spatial development, which posit substantial changes in spatial knowledge over the first six years of life (Landau 1996, 319).

Other investigators concluded that there is now

> . . . strong evidence of longterm continuity in process across the span from 2–3 years to adulthood, [in sharp] contrast with other prominent accounts of the development of spatial memory (Spencer and Hund 2003, 473).

Moreover, the skills of spatial thinking, like those of mathematical or verbal reasoning, appear to be at least somewhat cumulative. People who begin to develop mastery of spatial-thinking skills in early childhood will be able to use those skills to acquire and organize additional information throughout their lives (Gregg 1999; Uttal 2000).

We conclude with a tantalizing quote from a very recent book on memory formation. After summarizing a series of experiments dealing with spatial memory, involving laboratory studies with mice and rats as well as observational studies with chimpanzees and human beings, Eric Kandel, a Nobel Prize winner, concluded:

> We found that even ambient attention is sufficient to allow a spatial memory to form and become stable for a few hours, but such a [mental] map becomes unstable after three to six hours. . . . [but if] forced to pay a lot of attention to a new environment, by having to learn a spatial task at the same time as it is exploring the new space, the spatial map becomes stable for days (Kandel 2006, 312).

One might reasonably infer that durable learning of geographic information is more likely to occur when lessons are explicitly designed to "force" students to perform a spatial task, that is, to use one or more of the distinct modes of spatial thinking that appear to be at least partially "hard-wired" into the human brain. As we said at the end of our recent review of spatial-cognition research: "students would therefore benefit if spatial-thinking skills had a more prominent place in the curricula and assessment programs of American schools" (Gersmehl and Gersmehl 2006). In this article, we have extended that review by summarizing a substantial body of recent research that clearly supports adding six words to the end of that sentence: "starting in kindergarten and first grade."

NOTE

1. In this article, we suggest specific terms to label each different mode of spatial thinking, but it is important to note two things. First, our list is based on a survey of research done in a number of different disciplines, including neuroscience, developmental psychology, linguistics, robot engineering, and architecture, as well as geography and geographic information systems. Second, those disciplines do not even agree on a term for the categories. We use "modes" as our category identifier, but other articles may use aspects, elements, forms, kinds, skills, types, or ways to denote the same basic idea. We also have prepared a list of synonyms for the other terms on the list, which we would be glad to share with anyone who sends an e-mail request.

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