CHAPTER 15

Three Kinds of Spatial Cognition

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INTRODUCTION

Scientific inquiry works best when scientists focus on *natural kinds*. That is, scientific progress depends on grouping together objects and phenomena that share deeper properties and important underlying characteristics. Chemistry advanced considerably when Mendeleev grouped elements so as to highlight their underlying structures, thus allowing him to predict the existence and properties of elements not yet discovered; biology took a giant step forward when Linnaeus delineated a hierarchical taxonomy for biological species that revealed relevant underlying characteristics and that structured the multitude of observations of biological phenomena from the general to the specific. Of course, the periodic table and Linnaean classification were enriched and altered as understanding of chemical and biological principles grew, but their formulation provided valuable initial leverage.

Does psychological science concern natural kinds? In many areas of psychology, there is doubt. For example, diagnosis of mental disorders has arguably concentrated excessively on surface symptoms while failing to group together problems based on their underlying pathologies, putting psychology into what Hyman (2010, p. 157) called an *epistemic prison*. In addition, everyday language may not capture natural kinds in human emotions or social interaction (Barrett, 2006), although there are novel proposals (Mitchell, 2009). However, other areas of psychology have established more secure foundations. For example, efforts to refine the folk concept of *memory* by postulating distinct types of memory (Squire, 1992; Tulving, 1972) have borne considerable empirical fruit, and efforts to analyze language as consisting of distinct neural and computational processes have led to increasingly sophisticated understanding of language as an interconnected system of parts (Poeppel & Hickock, 2004).

This chapter is organized around the argument that spatial cognition is *not* a natural kind. Humans act in two distinct ways in the spatial world: We navigate, and we manipulate objects. The two modes have different evolutionary roots and distinct neural bases, albeit with some interconnections. Navigation is a function necessary to a broad array of mobile species and it draws on various subsystems relevant to location and movement tracking, integrating those systems in various ways. These systems require orientation to the external world, that is, extrinsic coding between and among objects and landmarks, including the self. Object manipulation for humans involves far more than simply holding objects: Our species has evolved to use and invent tools, a development that involves the mental representation and transformation of the shapes of objects, that is,

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intrinsic coding. There is also a third kind of spatial cognition: As a symbolic species, we can spatialize thought in various symbolic ways, using tools such as language, metaphor, analogy, gesture, sketches, diagrams, graphs, maps, and mental images. In this broader sense, spatial thinking is pervasive in human cognition across multiple domains.

Why have investigators been content to use the term *spatial cognition* if it isn't a natural kind? One simple reason is that any kind of action in a spatial world is in some sense spatial functioning, and hence can sensibly be called spatial cognition, as can metaphoric extensions of spatial categories (Lakoff & Johnson, 2008). Another potential justification involves what spatial thinking does *not* seem to require, that is, the intuition that spatial thinking, unlike many other kinds of thought, does not necessarily involve verbal description. Indeed, more than a century's worth of psychometric data points to the separation of spatial and linguistic intelligence, based on factor analyses aimed at defining the structure of intelligence. Thus this chapter will begin by considering the contribution of this research tradition. We will also look at its limitations. Although psychometric data provided one of the central pillars leading to the conceptualization of spatial cognition as a single domain, efforts in this tradition have failed to provide a clear and satisfying typology of various kinds of spatial thinking (Hegarty & Waller, 2005), despite many attempts to do so (e.g., Linn & Petersen, 1985).

The remainder of the chapter considers the reasons for considering spatial cognition as being composed of three distinctive domains, and what is gained thereby. There are evolutionary, behavioral, and neural arguments for the basic distinction between navigation and object manipulation; symbolic uses of space are clearly different from either, although they may describe the relations encoded in service of each. We also discuss heterogeneity within domains, themes that crosscut domains, controversies, and future directions.

THE VIEW FROM PSYCHOMETRICS

The enterprise of intelligence testing began with the atheoretical curiosity of Francis Galton, changed into Alfred Binet's work to answer questions the government of France posed about schools, and continued to flourish in other applied venues, such as military selection, during World War I. This history has supplied us with a wealth of fascinating data about human intellect. However, the research antedated the development of a theory of human cognition, and this fact had a variety of unfortunate consequences for developing taxonomy for spatial thinking. There were several problems, all very understandable, given the historical context. First, the tests had to be devised intuitively, based on trial-and-error approaches to finding tasks for which performance could be measured reliably and which also showed variation that validly predicted outcomes. Development of theory lagged behind for many reasons, including the fact that many modern methodologies had not yet been developed, such as measurement of reaction times, eye movements, and neural activation. Second, the tests also had certain practical constraints. For group testing, they had to be reasonably easy to understand from written instructions and able to be completed in a paper-and-pencil multiple-choice format. Even with individual testing, the amount of materials that could be used was limited, and time was limited too. Nevertheless, some interesting spatial tasks were typically included in the testing array, with more tests devised throughout the 20th century, until the list of spatial tests reached into the thousands, as compiled in the *International Directory of*

Spatial Tests (Eliot & Smith, 1983). Given how many spatial tests were around, what could possibly be missing?

There were at least three serious limitations, despite the abundance of tests, which stemmed from the historical context and the methodological and practical limitations just mentioned. One issue was that the skills could not be analyzed componentially so as to define the cognitive processes underlying them. Thus, the task of delineating the commonalities and differences among the various tests could only be tackled with the blunt instrument of factor analysis. Another issue was that there was no systematic means of surveying the kinds of spatial skills that people use in their everyday lives. In the end, the tests that psychometricians designed intuitively missed whole kinds of spatial skill. Perhaps most crucially, it was impossible to assess navigation using the technology available 100 (or even 20) years ago. Testing large numbers of people outdoors was clearly not practical, nor could one test people indoors in large-scale standardized environments. The Guilford-Zimmerman Spatial Orientation Test hinted at navigation, with its requirement to imagine the tilt of a boat and its orientation to the shore from line drawings of the prow (Guilford & Zimmerman, 1948), but even so, it did not require finding novel routes and detours or representing the relations among multiple environmental landmarks.

These three problems collectively impose severe limitations on what we can conclude from over a century of psychometric data. Despite these problems, however, we have learned some valuable facts. First, a great deal of data converges on the idea that spatial functioning is a distinct aspect of human intellect, as suggested by Figure 15.1. A variety of spatial measures are highlighted in the top sector, one of the three principal sectors, along with verbal thinking in the lower left and mathematical thinking in the lower right. Second, the gradations from the inner to the outer circles show us that some tests are more general (and thus less specifically spatial) than others, and, vice versa, some tests are more specifically spatial. For instance, geometric analogies are in the same pale inner circle with verbal analogies and number analogies, due to the centrality of analogical reasoning to human intelligence (Gentner, Holyoak, & Kokinov, 2001). Analogical reasoning is a kind of reasoning that is abstract and general, and that can be symbolically represented, so its centrality in this diagram highlights the kind of spatial thinking that we previously called the "third kind." By contrast, tests that involve mental rotation (Cubes, Flags, Cards) are in the outer sector. These tests tap skills that are more distinctly spatial. They exemplify skills related to tool use because they are most useful when thinking about the structural descriptions of individual objects at a scale that allows manipulation with the human hand, and hence these tests are less linked to other tests. Notably missing are tests of navigational skill.

Would tests not included in the typical battery cluster similarly or differently? We simply do not know. The groundbreaking work of Roger Shepard and his colleagues on mental rotation and paper folding paved the way for componential analysis (for an overview, see Shepard & Cooper, 1986), and soon afterwards, the availability of a multiple-choice test of mental rotation that used Shepard's block stimuli (Vandenberg & Kuse, 1978) supported individual-differences research. However, the test was never added to standard psychometric batteries, and thus its more fine-grained analysis of rotation skills was not included in factor analyses. Furthermore, efforts to better characterize small-scale spatial skills not addressed by conventional tests, such as cross-sectioning, have only appeared recently. Other recent developments have been efforts to devise a

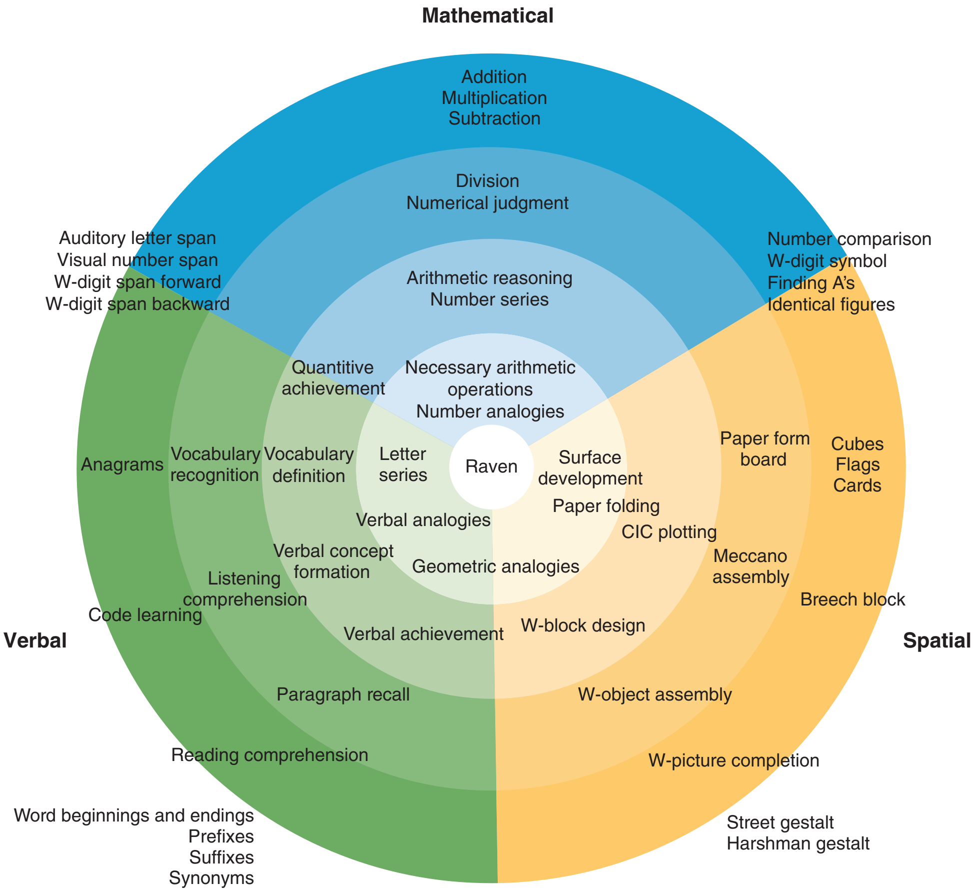

Figure 15.1 Spatial functioning is a distinct aspect of human intellect. Spatial measures are highlighted in the gold-colored sector of this model, along with verbal and mathematical thinking. Tests toward the center are more general; those towards the periphery are more specific. W in figure refers to Wechsler (i.e., taken from the Wechsler intelligence test).
SOURCE: Gray and Thompson (2004) (adapted from Snow, Kyllonen, and Marshalek, 1984). Reprinted with permission of Macmillan Publishers Ltd.

reliable and valid objective test of navigation ability and to expand our characterization of abstract spatial thought.

A NEW TYPOLOGY

One way to conceptualize the crucial difference between navigation and object manipulation is that navigation concerns the *extrinsic* spatial relations among objects, with wider frames of reference, whereas object manipulation acts upon the *intrinsic* spatial relations that constitute the structure of objects. The distinction between extrinsic and intrinsic relations is one key aspect of recent proposals about the structure of spatial skills, illustrated in Figure 15.2 (Newcombe & Shipley, 2015; Uttal et al., 2013).

One possible question about treating the difference between navigation and object manipulation as the difference between

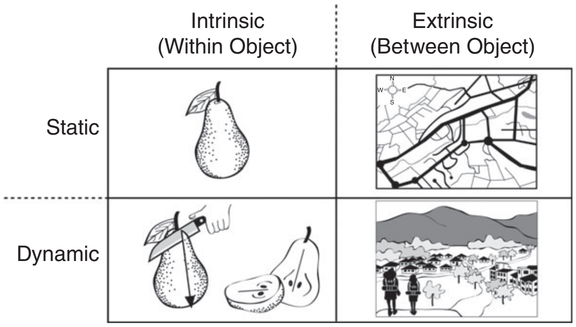

Figure 15.2 Examples of dividing spatial cognition into the static and dynamic aspects of intrinsic and extrinsic spatial relations.

extrinsic and intrinsic spatial coding is that manipulating object representations often seems to require an external reference point; for example, the mental rotation of a block figure has meaning only with respect to the observer (or some other landmark), which defines the rotation. However, object manipulation requires orientation with respect to only a single point, typically nearby and often a static observer, or even more specifically, the observer's eyes and hands. By contrast, navigation draws on representations involving multiple entities usually spread over a wide scale, encoding relations among external landmarks for effective allocentric representation, and/or representing the moving self, with updates on direction and heading gained from the internal senses (e.g., Burgess, 2006; Sholl, 1996).

A second distinction, crosscutting to intrinsic and extrinsic coding, was also proposed by Newcombe and Shipley (2015), and by Uttal et al. (2013). This contrast is between static and dynamic thinking. It is basically the classic contrast that cognitive psychology has long made between representation and transformation (i.e., acting upon mental representations to transform them) and harks back to Shepard's analyses of mental rotation, in which he identified the slope of the function relating degrees of rotation to reaction time as indexing the dynamic process of mental rotation itself, and the y-intercept as indexing encoding and decision time. Static encoding is prerequisite to dynamic transformation: Spatial relations need to be represented or encoded in order to be transformed dynamically. This relation may be unidirectional, at least for intrinsic coding: Recognition of objects does not require mental rotation (Farah & Hammond, 1988).

Figure 15.2 gives some illustrations of the proposal to divide spatial cognition into the static and dynamic aspects of intrinsic and extrinsic spatial relations. In a static-intrinsic coding of object structure, we represent the shape of something; for example, a pear. In a dynamic-intrinsic transformation, we predict the appearance of the pear after it is cut. We could also imagine rotating it. If we replaced the pear with a more malleable figure, such as a clay sculpture, we could also imagine slicing it and sliding the two pieces along the slice, or we could imagine deforming it plastically. If it were a brittle object such as a clay pot, we could imagine smashing it. In a static-extrinsic coding of object location, we represent where objects are with respect to each other, to external spatial frameworks including landmarks, slope of the land or the cardinal directions, and to the self. These objects are typically large-scale objects within which we are typically contained, such as houses, rather than small objects that we can hold. In a dynamic-extrinsic transformation, we predict what we might see from another vantage point, as when we approach a village along different roads, or circumnavigate a mountain range. We can also imagine an overall map, in which we integrate across frameworks to infer how the layout of the town is situated with respect to a mountain valley not visible from the town itself.

There are several arguments for splitting spatial cognition into navigation (extrinsic spatial relations) and tool use (intrinsic relations), based on evolutionary considerations, behavioral research, and neural data.

Different Evolutionary Roots

Psychology has a spotty history in using knowledge about evolution and data from comparative cognition research to build theory. Evolutionary psychology is often controversial, when it is construed to imply sociobiological guesses about ways in which phenomena such as mate choice or altruism depend on reproductive advantage. But there are more powerful ways to use an evolutionary framework. Thinking about evolution and cross-species comparison can be very productive in delineating the structure of human intellect, yet has generally been rarely utilized, except for discussion of the degree to which human language is species specific. This situation is changing, however, as data accumulate on a wide variety of nonhuman animal species, studied both in the field and in the laboratory.

Fortunately, navigation has been studied comparatively for many decades (e.g., Wiener et al., 2011). It is widely recognized that all mobile species have to solve the problem of finding their way around the world. A great deal of research exists on a wide variety of species, including insects such as ants and bees, birds such as homing pigeons and migrating birds, and various mammals, including humans. Much of this research has utilized common paradigms such as the Morris (1984) water maze or the Cheng (1986) reorientation task, so that comparative claims can be made with increasingly greater precision. From these facts alone, we might conclude that navigation is special, because there appears to be an evolutionarily conserved neural apparatus for accomplishing this vital goal, although there is also variation, even with closely related species, depending on the navigational demands of the environment of adaptation (Rosati & Hare, 2012).

In contrast to the species-general need to navigate, a species-specific aspect of human anatomy is the opposable thumb, and a unique attribute of humans is their invention and use of tools. Although tool use and even tool invention has been observed in a few other species, such as corvids and macaques (e.g., Cheke, Bird, & Clayton, 2011; Hihara, Obayashi, Tanaka, & Iriki, 2003; Weir, Chappell, & Kacelnik, 2002), these amazing phenomena usually involve naturally available objects such as stones and sticks rather than carefully crafted objects kept handy for future use. In addition, birds can only manipulate objects with their beaks, a fact that limits their facility with crafting objects. Monkeys have hands but they are not as adapted as the human hand for grasping objects. However, tool invention requires more than the opposable thumb: It also rests on the development of the neocortex (Reader & Laland, 2002) and the appearance of neural networks for representing the actions of conspecifics (Hecht et al., 2013). Invention, as opposed to imitation, of tools may rest on the ability to encode the structure of naturally occurring objects and then imagine how they might be transformed by cracking, folding, chipping, and the like to achieve desired ends. Indeed, when transformations of object structure have been studied in nonhuman species, it has been very difficult to document that it occurs at all. Primate species have shown complex patterns not entirely consistent with mental rotation, even after considerable training (Hopkins, Fagot, & Vauclair, 1993; Köhler, Hoffmann, Dehnhardt, & Mauck, 2005; Vauclair, Fagot, & Hopkins, 1993). The linkage between mental rotation and the structure of the human hand is further supported by findings indicating motor involvement in mental rotation, especially prominent earlier in development, but often evident in adults as well (e.g., Frick, Daum, Walser, & Mast, 2009; Wohlschläger & Wohlschläger, 1998).

In terms of abstract spatial thinking, the claim that language is species specific is now widely accepted, even though precisely what is specific and how language fits into evolution continues to be debated (Hauser, Chomsky, & Fitch, 2002; Pinker & Jackendoff, 2005). Of course, language includes spatial language, and a wider claim is that symbolic spatial thinking is distinctively human, including thinking using symbols that are nonlinguistic. There are some data to support this idea. For example, even chimpanzees show only a fragile ability to use simple scale models provided for them by humans (Kuhlmeier & Boysen, 2001; Kuhlmeier, Boysen, & Mukobi, 1999); there is no convincing evidence of robust use, let alone invention, of maps or models, even by our closest primate relatives. On another front of spatial-symbolic reasoning, there is some debate about whether any species of great apes can map spatial relations or use analogical reasoning, but the consensus again is that such capabilities are fragile and in crucial ways different from those of humans, including human children (Christie, Gentner, Call, & Haun, 2016; Haun & Call, 2009; Hribar, Haun, & Call, 2011).

Distinguishing Behavioral Characteristics

Evolutionary arguments are suggestive, but they do not provide the kind of hard data that experimental psychology demands. As cognitive psychology was being established in the 1960s and was developing apace in the 1970s and after, its methods were applied to spatial thinking. As already mentioned, Roger Shepard and his colleagues began their line of research on chronometric analysis of mental rotation and other spatial tasks, such as paper folding (Shepard & Feng, 1972; Shepard & Metzler, 1971). In cognitive development, inspired initially by Piaget, researchers began to study perspective taking, where Piaget had done pioneering work on the Three Mountains problem (Piaget & Inhelder, 1948/1956), as well as to do research on mental rotation, inspired both by Piaget's (Piaget & Inhelder, 1966/1971) and by Shepard's work. Researchers debated whether perspective taking was evident earlier than Piaget claimed (Flavell, Flavell, Green, & Wilcox, 1980; Newcombe & Huttenlocher, 1992), and the same debate raged around mental rotation (Dean & Harvey, 1979; Estes, 1998; Marmor, 1975, 1977).

This work began to reveal a puzzling pattern. Mental rotation of an array of objects and taking the perspective of another observer on that same array are computationally equivalent—for an artificial intelligence or in terms of formal logic. Nevertheless, for humans, there turned out to be empirically dissociable cognitive operations, showing different signature patterns of ease and difficulty (e.g., Hegarty & Waller, 2004; Huttenlocher & Presson, 1973, 1979; Kozhevnikov & Hegarty, 2001; Ratcliff, 1979; Wraga, Shepard, Church, Inati, & Kosslyn, 2005; Zacks, Vettel, & Michelon, 2003; for a review, see Zacks, Rympa, Gabrieli, Tversky, & Glover, 1999). It was not simply that one or the other operation seemed to be easier. In fact, there was sometimes an advantage of perspective taking over array rotation, but also vice versa depending on the nature of the task (Huttenlocher & Presson, 1973, 1979; Simons & Wang, 1998; Wang & Simons, 1999; Wraga, Creem, & Proffitt, 2000; Wraga et al., 2005).

The functional distinction between mental rotation and perspective taking points the way to distinguishing between object use and navigation. Array rotation is akin to the mental rotation of a single object studied by Shepard, an object that could be held in the hand (or be imagined as being held). By contrast, asking a question about perspective involves imagining walking around an array and looking at it from another vantage point, as would be typical during a navigation task. Experimenters who naturally aimed to keep task elements constant often tried to equate array rotation and perspective taking by having participants examine a small grouping of objects on a tabletop. In retrospect, we can now argue that such arrays did not constitute prototypical rotation tasks, in which an object could be manipulated by hand, although occasionally the array was placed on a platform that allowed for it to be rotated with a handle. Nor did the arrays generally allow for the kind of perspective taking that occurs during navigation, where objects wholly, or at least partially, occlude each other, and the various views need to be integrated over the time needed to walk lengthy distances. Indeed, in terms of navigation, a notable (and somewhat disturbing) fact about all the tasks was that they used small-scale spaces.

Scale is a crucial consideration when considering how to carve up spatial cognition. Montello (1993) categorized scale into four levels: figural, vista, environmental, and geographical. Figural and vista spaces are small-scale environments, but only figural space highlights the structural description, or intrinsic coding, of objects. The intra-object locations of a toy car's windshield and tires are an example of figural space. Although still small-scale, the inter-object locations of the car, the table supporting it, and the surrounding chairs are an example of vista space. Figural and vista spaces share the characteristic that there is no need for action to acquire knowledge of the various parts and their spatial relations—everything is visible from a single vantage point. Environmental and geographical spaces refer to spatial arrays too large to be encoded from a single viewpoint, thus requiring some form of movement to acquire global spatial knowledge. Both are large-scale environments, but environmental space can be explored on foot whereas geographical space exceeds the bounds of natural human locomotion (Tatler & Land, 2011). The layout of a city, for example, is an example of environmental space, whereas the relative position of states, countries, and continents constitute geographic space.

Going back to array rotation and perspective taking: They have been primarily studied in vista spaces, whereas figural space is more typical for object manipulation, and environmental and geographic space is more typical for navigation; that is, action immersed within the array (Chrastil & Warren, 2012, 2013). In the real world, we often move objects in our hands to learn about them, and we move around large-scale environments to acquire information for navigation. Rotation and perspective taking are equally good ways to learn about fairly simple spatial relations in vista space; in fact, it is sufficient to passively observe the visual transitions to learn more than when the array is shown in successive static snapshots—although note that in the real world, especially before the advent of technology, such experiences would have been rare (Holmes, Marchette, & Newcombe, in press). But in a situation more similar to large-scale spaces, in which people need to integrate a large number of spatial relations over multiple views, perspective taking is best, consistent with the idea that perspective taking is distinctively navigational (Holmes & Newcombe, 2016).

Distinct Neural Bases

Evolutionary arguments are suggestive of the existence of three kinds of spatial cognition, and behavioral evidence has hinted at the importance of a distinction between object-centered and navigational thinking. However, findings from neuroscience provide the strongest support for this distinction. Of course, modern imaging techniques have only been available relatively recently. But neuropsychology research with patients was sufficient to show that patients suffering from navigational challenges did not typically have more widespread problems, and that problems in recognizing and manipulating objects could be similarly distinct. Indeed, we have known for 20 years or more that patients with brain damage that caused navigational deficits might not have other problems, including problems in spatial tasks of the kind related to object manipulation (Kim et al., 2013). Furthermore, patients who have navigational problems can be subdivided into groups with even more specific problems than simply getting lost, such as problems representing the locations of objects relative to themselves following damage to posterior parietal cortex, or PPC (Aguirre & D'Esposito, 1999), problems representing locations relative to other locations following damage to retrosplenial cortex (Aguirre & D'Esposito, 1999; Maguire, 2001), poor recognition of familiar landmarks following damage to parahippocampal region (Epstein, DeYoe, Press, Rosen, & Kanwisher, 2001), or various kinds of navigation problems following damage to the hippocampus (Guderian et al., 2015). Similarly, people with deficits centered on encoding object structure often do not show other deficits and can be subdivided into even more specific groups. There is wide diversity in the specific ways in which object recognition can be impaired in agnosia (Farah, 1991, 2004), in which visual imagery can be impaired and spatial imagery preserved (Farah, Hammond, Levine, & Calvanio, 1988), and in which mental rotation of hands can be impaired while mental rotation of external objects is preserved, or vice versa (Tomasino, Toraldo, & Rumiati, 2003).

Thus, spatial deficits are actually as various as the types of aphasia that have suggested a delineation of components of the language system. But definitive evidence of specificity and further delineation of subsystems of a navigational system and an object encoding system have come from modern neuroscience. We have now made impressive progress in delineating the neural components of a navigation system at a variety of grain sizes from a cellular to a systems perspective, and in formulating computational models of how the neural hardware supports representations and behavior.

As a side note, this happy state of affairs is realizing David Marr's (1982) dream that cognitive science can relate the computational, representational, and implementational levels of analysis. There are several reasons for this success. First, we are dealing with well-defined problems. For navigation, if you are here and want food, where do you wish to go and what route would you take to accomplish getting there? Similarly, for object manipulation, if you slice an orange vertically, you will see one predictable configuration, and if you slice it along its equator, you will see a different structure. Such clarity has favored the development of a variety of interesting behavioral paradigms within which we can examine neural properties and about which we can formulate computational models. Second, the fact that navigation is a cross-species demand has allowed for multipronged converging attacks on the problem using a variety of techniques and species, rather than limiting the focus of investigation on the human species, with associated methodological limitations. Of course, we lack the leverage of commonality for object manipulation, but here we have the advantage of contrasts between human capacity and the capacity of nonhuman species to lay bare our unique characteristics.

Navigation

At the cellular level, the initial step in establishing the neuroscience of navigation was the discovery of place cells in the rodent hippocampus; that is, cells that fire whenever the animal is in a certain place within an enclosure (O'Keefe & Dostrovsky, 1971); place cells were also eventually found in other parts of the rodent brain as well as in the hippocampus. Soon after the discovery of place cells, O'Keefe and Nadel (1978) published a book with the memorable title of *The Hippocampus as a Cognitive Map*. The existence of place cells in the human brain has been confirmed, although not until over 30 years after the initial discovery, in studies of human patients with epilepsy undergoing monitoring in preparation for surgery (Ekstrom et al., 2003). Although the discovery of place cells was important, more was needed: Place cells are clearly necessary, but not sufficient, for an accurate map of the environment. There are at least two other important elements. First, we need to know which direction we are facing—consider the situation when a blue dot on a map shows your current location, but you do not know which way to head unless you also are oriented to your surroundings. It turned out that the brain also has head-direction cells (Taube, Muller, & Ranck, 1990a, 1990b). Second, we need a coordinate system that relates places and directions to each other, and it turned out that the brain has grid cells arranged in hexagonal patterns that allow for precise positioning (Fyhn, Molden, Witter, Moser, & Moser, 2004; Hafting, Fyhn, Molden, Moser, & Moser, 2005; Sargolini et al., 2006). There is now a large literature on place cells, head-direction cells, and grid cells, as well as other cell types, such as border cells (Solstad, Boccara, Kropff, Moser, & Moser, 2008) and boundary vector cells (Lever, Burton, Jeewajee, O'Keefe, & Burgess, 2009). Taube (2007) has presented an overview of the navigation system that shows the high level of interconnectedness and the ways in which there are many opportunities to integrate information from various informational sources, including self-motion and external landmarks.

At the systems level, we have already seen that neuropsychological and cellular evidence implicates the hippocampus, parahippocampus, retrosplenial cortex, and PPC as major loci in a functional navigation system. Over the past two decades, each region has been extensively studied in humans using functional magnetic resonance imaging (fMRI) techniques. Of course, a limitation of imaging studies is that people cannot move in the scanner, but researchers have made clever use of exposure outside the scanner coupled with photographs or video to study the navigation system. For example, Epstein and Kanwisher (1998) discovered and labeled the parahippocampal place area (PPA), which responds selectively to photographs of scenes rather than to objects or faces. Such scenes can be in rural or urban environments, and can even include tabletop scenes made out of blocks (Epstein, Harris, Stanley, & Kanwisher, 1999). The main function of the PPA seems to be to recognize local scenes, with retrosplenial cortex (also called the retrosplenial complex) supporting mechanisms that orient scenes in the broader environment and to each other (Epstein, 2008). To give just a few other examples from this very active area of research, Doeller, King, and Burgess (2008) delineated hippocampal and striatal circuits for the representation of landmarks and boundaries; Marchette, Vass, Ryan, and Epstein (2014) provided data on anchoring the neural compass; and Shine, Valdés-Herrera, Hegarty, and Wolbers (2016) provided a somewhat different view of the neural compass in work on coding of head direction in retrosplenial cortex and the thalamus.

There are several models of how the main brain areas interact (e.g., Byrne, Becker, & Burgess, 2007; Ekstrom, Arnold, & Iaria, 2014). However, in the context of formulating a typology of human spatial cognition using neural data, the main question is not formulating a precise model, as important as that goal is to understanding navigation, but evaluating to what extent the circuits identified for navigation overlap with what we know about the neural substrates of performance in object-centered tasks such as mental rotation. So we turn now to examine the neural substrates of object encoding and transformation.

Object Representation and Transformation

The available studies of the neural substrates of this kind of spatial cognition concentrate almost exclusively on mental rotation. Zacks (2008) performed a meta-analytic review of the available fMRI studies of rotation, with an eye to providing a consensus on how the neural evidence gives us a purchase on the hypothesis of analog spatial representations rather than purely propositional ones, and on the role of motor processes. The conclusions were quite clear. One area consistently activated across studies was PPC, centered on the intraparietal sulcus, supporting the hypothesis of analog spatial representations. Another area activated was the precentral sulcus, supporting the hypothesis of motor involvement.

There are only very sparse data on tasks other than mental rotation. For example, mental folding may also involve activation in the parietal lobe, although we do not have good localization information because event-related potential, not fMRI, has been used in examining this task (Milivojevic, Johnson, Hamm, & Corballis, 2003). Why are there so few studies of other tasks? The focus might be thought to stem from the fact that Shepard's work established an elegant paradigm that could be used to decompose mental rotation into component processes. But similar componential work was done for other tests of object manipulation and transformation, including paper folding (Shepard & Feng, 1972), cube comparisons (Just & Carpenter, 1985), and the Minnesota Paper Form Board test (Mumaw & Pellegrino, 1984), so the availability of paradigms was not the only determinant in the focus of the imaging work. An additional impetus for the neural work on mental rotation came from the imagery debate (e.g., Kosslyn & Pomerantz, 1977; Pylyshyn, 1973). Investigators wanted to know whether brain data suggested that visual and spatial imagery was really verbal or propositional, or more specifically visual or spatial. But that debate was not confined to mental rotation, but rather ranged widely over various kinds of static and dynamic visual imagery. It is possible that the neural research focused on mental rotation because there was also interest in the hypothesis that mental rotation involved covert motor processes.

Whatever the historical reasons for the focus on mental rotation, there is an important gap in our knowledge, given the large body of behavioral data on the contrast between mental rotation and perspective taking; namely, that we do not have much information on the neural bases of perspective taking. One clue that perspective taking may engage navigational systems rather than the same systems engaged by mental rotation comes from an fMRI adaptation study done by Epstein, Higgins, and Thompson-Schill (2005). Participants viewed scenes while in the scanner. In the viewpoint change condition, they saw scenes from different vantage points, just as they might be asked to imagine in perspective-taking tasks. One of the parts of the navigation system, the parahippocampal cortex, was initially very viewpoint specific, but became more viewpoint invariant over time. Interestingly, this change was more evident in people who rated themselves as better navigators on the Santa Barbara Sense of Direction scale (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). More recently, and crucially, Lambrey, Doeller, Berthoz, and Burgess (2012) studied the contrast between imagining a tabletop array of objects rotating versus imagining walking around the array in an fMRI experiment. They found that perspective taking activated areas involved in the navigation system, such as retrosplenial cortex and hippocampus, whereas array rotation was associated with activation of the right intraparietal sulcus. This experiment clarifies and substantiates the behavioral research comparing rotation and perspective taking, and very clearly supports the distinction between object manipulation and navigation.

NAVIGATION: CURRENT KNOWLEDGE, FUTURE DIRECTIONS

There has been an explosion of research on navigation, and an overview chapter can only hint at how much is known and what remains to be discovered. This section will concentrate on cognitive maps, for two reasons. First, the term has caught the imagination ever since Tolman's (1948) paper and was strengthened by O'Keefe and Nadel's (1978) use of the term. But it has always been controversial. Despite the fact that navigation is vital for survival and reproduction, and thus it would be natural to expect that we would be able to accurately encode the spatial environment, human spatial judgments show odd biases, and even outright incoherencies. For example, we use heuristics for spatial judgments both at geographic scale (e.g., Stevens & Coupe, 1978; Tversky, 1981) and at environmental scale (Bailenson, Shum, & Uttal, 2000; Hirtle & Jonides, 1985; Tversky, 1981; Uttal, Friedman, Hand, & Warren, 2010). Even worse, spatial judgments sometimes show asymmetries; that is, judging a distance from point A to point B as different from the distance from point B to point A (Baird, Wagner, & Noma, 1982; Holyoak & Mah, 1982; McNamara & Diwadkar, 1997; Sadalla, Burroughs, & Staplin, 1980), and participants in virtual reality experiments may not be able to diagnose that they are in impossible environments (Kluss, Marsh, Zetzsche, & Schill, 2015; Warren, Rothman, Schnapp, & Ericson, 2017; Zetzsche, Wolter, Galbraith, & Schill, 2009). Based on such findings, there are proposals that our spatial representations are nonmetric or even associative (Foo, Warren, Duchon, & Tarr, 2005; McNamara, 1991; Tversky, 1981). As Tversky (1981, p. 432) put it: "Cognitive maps may be impossible figures."

There are counterarguments, however. For example, the categorical adjustment model (CAM) of spatial location coding proposed by Huttenlocher, Hedges, and Duncan (1991) can explain asymmetries in spatial judgment (Newcombe, Huttenlocher, Sandberg, Lie, & Johnson, 1999). Perhaps more constructively, recent models are starting to suggest rapprochements. There may be locally metric representations with broad directional relations among them (Chrastil & Warren, 2013, 2014; Jacobs & Schenk, 2003; Kuipers & Byun, 1991). Alternatively, there may be various maps at multiple levels of scale, with techniques for combining across scale, as suggested by findings on scaling of grid cells (Giocomo, Zilli, Fransén, & Hasselmo, 2007) and as now implemented in robotics (Chen, Lowry, Jacobson, Hasselmo, & Milford, 2015)

A second reason to pay special attention to cognitive maps is that, recently, a new approach to the question of whether they exist has been suggested. In this individual-differences perspective, some people may form cognitive maps, but not everyone. Acknowledging such differences tips a hat to intuition (i.e., people discuss openly at cocktail parties whether they have a propensity for getting lost). It also has the merit of uniting cognitive psychology and neuroscience with the psychometric approach. In fact, objective assessments of navigation show pronounced variation among people (Schinazi, Nardi, Newcombe, Shipley, & Epstein, 2013; Weisberg & Newcombe, 2016; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014). This variation has become more open to study as changes in the cost and graphic design of virtual environments (VEs) have allowed the development of new tools.

One such tool, called Virtual SILCton, has been used with hundreds of participants of varying ages (Weisberg & Newcombe, 2016; Weisberg et al., 2014). Virtual SILCton is a desktop VE navigation paradigm comprising two main routes in different areas of the same VE and two connecting routes. In the testing phase, participants complete two tasks—a pointing task and a model-building task. Performance on the pointing task is subdivided into a within-route and a between-route pointing performance based on the position of the target building in relation to the participant's pointing location in the VE. Weisberg et al. (2014) found three groups of navigators based on the within- and between-route pointing performance—integrators (good within/good between), nonintegrators (good within/bad between), and imprecise navigators (bad within/bad between). Crucially, the existence of three types of navigators based on the pointing task has been validated using taxometric and cluster analyses. The integrators exceeded the latter two groups on mental rotation, spatial orientation, and spatial navigation ability as measured by the Santa Barbara Sense of Direction scale self-report questionnaire. But nonintegrators do have assets. Weisberg and Newcombe (2016) found that they had significantly higher spatial and verbal working memory scores as compared to the nonintegrators, which correlated with their within-route pointing performance. Different demands may be placed on working memory by between-route pointing. Blacker, Weisberg, Newcombe, and Courtney (2017) suggest that spatial-relational working memory is specifically correlated with developing between-route directional knowledge. There are also individual *preferences* in navigation, which are not identical to ability differences. Research using the dual-solution paradigm has assessed people's preferences for finding shortcuts (place learning) versus sticking to established routes (response learning, also in a VE paradigm. Place and response learning were long regarded as either-or phenomena (e.g., Restle, 1957; Tolman, Ritchie, & Kalish, 1946). More recently, we have learned that they depend on the hippocampus and the caudate, respectively (McDonald & White, 1994; Morris, Garrud, Rawlins, & O'Keefe, 1982; Packard & McGaugh, 1996). In humans, better navigators have larger (Maguire et al., 2000; Maguire, Woollett, & Spiers, 2006; Schinazi et al., 2013; Woollett & Maguire, 2011) or more active (Hartley, Maguire, Spiers, & Burgess, 2003) hippocampi and smaller or less active caudates. In line with these findings, Marchette, Bakker, and Shelton (2011) found that human participants' preference for a place-based strategy was positively correlated with the ratio of hippocampal to caudal activity during encoding. However, place learners were not better at finding goals, given that success was possible with either a place or a response approach. Another kind of preference may involve visual or verbal thinking, and recently Kraemer, Schinazi, Cawkwell, Tekriwal, Epstein, and Thompson-Schill (2016) found that verbal coding (whether a preference or experimenter manipulated) predicts landmark coding, whereas visual coding predicts coding relative directions.

Of course, the existence of cognitive maps is not the only major issue in research on navigation at the moment. There are lively controversies concerning the existence of a great many topics. Examples, with citations to a few representative articles or reviews, include the existence of a geometric module for spatial reorientation (Cheng, Huttenlocher, & Newcombe, 2013), how egocentric and allocentric information is combined by adults (Zhao & Warren, 2015a, 2015b) and during development (Nardini, Begus, & Mareschal, 2013; Nardini, Jones, Bedford, & Braddick, 2008), how and in what circumstances indoor spaces and outdoor spaces can be related to each other (Marchette et al., 2014; Shine et al., 2016; Vass & Epstein, 2013; Wang & Brockmole, 2003), whether VEs simulate real-world environments (Loomis, Blascovich, & Beall, 1999; Ravassard et al., 2013; Taube, Valerio, & Yoder, 2013), the existence of sex-related differences (Chai & Jacobs, 2009; Moffat, Hampson, & Hatzipantelis, 1998), whether individuals can improve their cognitive mapping abilities, and whether navigational thinking has real-world consequences for STEM learning.

OBJECT ENCODING AND TRANSFORMATION: CURRENT KNOWLEDGE, FUTURE DIRECTIONS

As with navigation, a complete discussion of object coding and transformation would require a chapter in itself. Simply reviewing what is known about mental rotation could indeed be the basis for a lengthy discussion. Hence, we concentrate on questions related to the proposed typology of spatial cognition, going on to briefly consider development, individual differences, and implications for learning.

Refining the Typology

A key question about the distinction between object coding and navigation is how it maps onto the well-known distinction between the *what* and the *where* systems (Goodale & Milner, 1992; Mishkin, Ungerleider, & Macko, 1983). A great deal has been written about *what* and *where*, or sometimes *what* and *how*, and the distinction undergirds a very influential approach to spatial language (Landau & Jackendoff, 1993). In fact, the taxonomy proposed in this chapter derived originally from a discussion by Chatterjee (2008), which built on the *what-where* distinction and reported new evidence from both normal individuals and patients.

However, information about *what* is linked to information about *where* in this conceptualization; that is, *where* is where an object is or where it is moving from and to. *Where* applies to small-scale interactions between objects and viewer, or small-scale relations between two objects, but does not apply to navigationally relevant scene recognition, relations to allocentric landmark frameworks, or use of distance and direction.

Thus, both kinds of information are part of the object coding and transformation system. Importantly, the involvement of posterior (or inferior) parietal cortex in the *where* system suggests egocentric definition with respect to the body. Although such reference is actually often a part of processes such as mental rotation, as we have mentioned, coding of this kind is part of, but insufficient for, effective navigation (Burgess, 2006). Tellingly, neural activation for representing paths of action of individual objects is *not* seen in navigationally relevant parts of the brain such as parahippocampal cortex, which was actually treated by Kable and Chatterjee (2006) as a control area. Indeed, Landau (2016) has now written a friendly amendment to the original Landau–Jackendoff proposal, in which she addresses the fact that the navigation system was omitted entirely from their approach. Landau (2016) presents an innovative hypothesis concerning what aspects of spatial language may draw on the navigation system, whose validation requires further research.

Another question about object encoding and transformation concerns characterizing each process and exploring whether there are varieties of each process and how encoding and transformation relate to each other. Despite the fact that we have had hundreds of spatial tests, we have not exhaustively or rigorously explored object-centered spatial skills. Recently, interaction with scientists who rely on spatial thinking has allowed psychologists to broaden their horizons. For example, geoscientists have to imagine a variety of rigid and nonrigid transformations (Ormand et al., 2014). A variety of the latter is the brittle transformation, in which some spatial region rotates or translates (or both) with respect to others, which may also move. A common example occurs when we break a piece of crockery, but, at a slower timescale, this kind of process occurs constantly over the history of the Earth. Resnick and Shipley (2013) devised a test of this kind of thinking, and showed that expert geologists performed better than comparison groups of organic chemists or English professors. Importantly, organic chemists did just as well as geologists on mental rotation (a skills required by their discipline), although English professors did worse here too. There are also other new assessments, for instance of cross-sectioning and penetrative thinking (Cohen & Hegarty, 2012) and of bending (Atit, Shipley, & Tikoff, 2013).

Of course, if there are many kinds of object-centered transformations, we invite the old question with which factor analysis struggled so mightily; namely, what is the internal structure of this domain? There is transfer between tasks such as mental rotation and mental folding (Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008), but the fact that expert chemists can be good at mental rotation and not so good at brittle transformation suggests distinctions, as does the fact that mental rotation shows substantial sex differences while mental folding shows small, if any, sex differences (Harris, Hirsh-Pasek, & Newcombe, 2013b). Various paths forward are possible. One method would be factor analysis with an expanded array of tests (Atit et al., 2013). Another kind of leverage may be provided by computational modeling. Building on work on sketch understanding (Forbus, Usher, Lovett, Lockwood, & Wetzel, 2011), Lovett and Forbus (2013) analyzed and simulated studies in mental rotation and paper folding, finding evidence that shape smoothing can be a helpful process in mental rotation but is not applicable to mental folding. A different but complementary kind of leverage could be provided by imaging studies of the two tasks, especially if behavioral and computational work has isolated key differences that could be the focus in the subtractive methodology typically used in fMRI studies, along the lines of Lambrey et al. (2012).

We also need to explore the relations between encoding and transformation. It is not clear how to assess static intrinsic coding. Tests such as the Embedded Figures Test or the Hidden Figure Test require people to analyze complex visual stimuli to find a target pattern hidden in the complexity; tests of perceptual closure like the Mooney Figures test asks people to guess what objects are shown when the focus is soft. However, none of these tests use insights from the rich literature on visual object recognition and image understanding (e.g., Biederman, 1987; Tarr & Bülthoff, 1998), despite evidence that object encoding may be key to mental transformation (e.g., Göksun, Goldin-Meadow, Newcombe, & Shipley, 2013; Lovett & Forbus, 2013). Perhaps isolated testing of such skills is not possible, given that the value of various kinds of coding may depend on the transformation to be performed.

Learning and Development

There is a practical reason to care about object encoding and transformation. Individual differences in spatial thinking of this kind are substantial, and they predict success in scientific and mathematical learning. The case for this idea used to rest on anecdotes from famous scientists and mathematicians; for example, the spatial thinking apparently involved in deducing the structure of DNA, and some cross-sectional correlations (e.g., Kozhevnikov, Motes, & Hegarty, 2007). But there is now evidence from several large longitudinal data sets, with good statistical controls, showing that spatial skills in high school predict choices of university disciplines and lifelong careers (e.g., Wai, Lubinski, & Benbow, 2009), spatial skills in kindergarten predict elementary school mathematical thinking (Gunderson, Ramirez, Beilock, & Levine, 2012), and tests assessing 3-year-old children's ability to copy two- and three-dimensional shapes predict kindergarten math skills (Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, in press). If spatial skills were fixed and unchangeable, these findings might not matter too much practically, but meta-analysis showed moderate to moderately large effect sizes for training spatial skills, for adults as well as children, for women as well as for men, and across a broad range of types of spatial skill (Uttal et al., 2013). Furthermore, the effects showed durability and transfer.

If these skills are important in learning, it is natural to want to know how they naturally develop. Early work on the development of mental rotation and perspective taking has already been discussed. However, in the past decade, a great deal of new work has appeared, tapping a wider array of spatial skills, including traditional skills such as mental rotation (e.g., Frick, Hansen, & Newcombe, 2013; Frick, Möhring, & Newcombe, 2014a) and perspective taking (Frick, Möhring, & Newcombe, 2014b), but also expanding to folding (Harris, Hirsh-Pasek, & Newcombe, 2013a), scaling (Frick & Newcombe, 2012), and understanding diagrammatic representation (Frick & Newcombe, 2015). At the same time, there is evidence suggesting substantial object transformation ability in infants (e.g., Moore & Johnson, 2008; Quinn & Liben, 2008). Yet there is a conundrum here. Children as old as 3 years often perform very poorly on tests for which babies supposedly have ability. This contradiction raises important issues concerning what developmentalists mean by competence, which appears in a variety of domains. Perception-action skills do not necessarily imply the presence of skills that can be used in cognitive tasks requiring prediction and inference (Frick, Möhring, & Newcombe, 2014a).

COMMONALITIES

A central argument of this chapter is that the cognitive systems and neural networks that support navigation and object-centered processes are distinct. However, there are also at least three common processes: the use of egocentric frameworks for both intrinsic and extrinsic representation and transformation, the use of combinations of quantitative and qualitative coding in both kinds of representations, and the use of Bayesian combination. In addition, mental scaling can allow for mentally transforming a navigation problem into an object problem and vice versa.

Egocentric Frameworks

We need to represent both objects and sets of landmarks with respect to egocentric frameworks as reflected in the fact that PPC is involved in both navigation and object transformation. That is, as Zacks (2008) pointed out for mental rotation, people need to situate a structural description of the object (in some format, though just what format has been debated; e.g., Hummel & Biederman, 1992; Tarr & Bülthoff, 1998) with respect to an environmental reference frame, probably including the body coordinates of the observer. In turn, models of navigation typically suggest that parietal areas are most useful for encoding egocentric information (e.g., Byrne et al., 2007). An overlap, but not an identity, of neural networks is important to remember in considering how we sometimes see correlations across navigational and object manipulation abilities. For example, J. N. is a person with developmental topographic disorientation, who was carefully studied with multiple behavioral tests and comprehensive neural imaging (Kim, Aminoff, Kastner, & Behrmann, 2015). J. N. also showed a significant impairment in speed of mental rotation and in performance on paper folding. How and why were these limitations linked? Kim et al. found an absence of adaptation effects in retrosplenial cortex, and weak functional relations between retrosplenial cortex and PPA, all part of the navigation system. However, as Kim et al. point out, there is strong connectivity between retrosplenial cortex and parietal cortex. J. N.'s pattern of deficits may suggest that there are common processes involved in transforming allocentric and egocentric frameworks in both navigation and object-based tasks. Similarly, we also see relations between mental rotation and navigation in research on typical participants, as mentioned in the discussion of individual differences in cognitive maps. Perspective-taking skills are good predictors of success in real-world navigation tasks (Schinazi et al., 2013) and in VEs (Weisberg & Newcombe, 2016), but mental rotation is also related to success in learning spatial layouts from VEs (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Weisberg & Newcombe, 2016). As with J. N., these correlations may reflect variation in the facility with which people transform egocentric into allocentric frameworks and vice versa.

Quantitative and Qualitative Coding

There are several converging proposals that revolve around the idea that there are two kinds of information about spatial location, variously called categorical or coordinate (Kosslyn, 1987), qualitative or quantitative (Forbus, 2011; Klippel, 2012), or fine-grained or categorical (Huttenlocher et al., 1991). Studies of these distinctions have often concentrated on small-scale stimuli arguably most relevant to object coding, such as dots in circles or two small objects located in proximity to one another. However, work in computer science on qualitative coding has ranged more widely over geographic stimuli (Klippel, 2012) and the research on fine-grained and categorical information in psychology has shown applicability to natural scenes, such as sand dunes, mountain scenes, and lakes (Holden, Curby, Newcombe, & Shipley, 2010) and to locations in the three-dimensional world (Holden, Newcombe, & Shipley, 2013; Pyoun, Sargent, Dopkins, & Philbeck, 2013; Uttal et al., 2010). Thus, both objects and navigationally relevant scenes can be carved up into regions or categories in which location can be encoded qualitatively, and more precisely using a mental coordinate system. These two kinds of encoding need to be combined, however, for optimal functioning in many circumstances, which takes us to the topic of Bayesian combination.

Bayesian Combination

Huttenlocher et al.'s (1991) CAM proposed a Bayesian model in which categorical information is weighted more heavily as the variability—and hence uncertainty—of fine-grained information increases. The result of such weighting is bias toward the location of the category prototype. In addition, category boundaries also exert effects, by truncating the distributions of locational uncertainty (Huttenlocher, Hedges, Lourenco, Crawford, & Corrigan, 2007). Overall, the effect of combining fine-grained and category information is to increase accuracy by constraining location given uncertainty, even at the price of introducing bias. The categories used in this process appear to be both perceptual and conceptual, with the conceptual categories developed through expertise invoked only when they serve to tighten the perceptual categories (Holden, Newcombe, Resnick, & Shipley, 2015). CAM is similar to Bayesian models of sensory combination and its development (e.g., Ernst & Banks, 2002; Nardini et al., 2013). Especially noteworthy is that Bayesian models of combination of various kinds of spatial information are becoming more common, focusing especially on combinations of path integration and landmarks (e.g., Nardini et al., 2008; Zhao & Warren, 2015a, 2015b). An overview of CAM and its relation to other Bayesian approaches to spatial behavior explains this family of approaches in more detail (Cheng, Shettleworth, Huttenlocher, & Rieser, 2007).

Scale Translation

An object can, in principle, be defined at any scale, although some objects are privileged by virtue of being the entities that humans naturally manipulate in their everyday lives. But we can also imagine, in the context of a specific spatial task, that entities too small or too large to ever actually be manipulated are indeed manipulable objects (e.g., too small to hold—an atom, a molecule, a bacterium; too large to hold—a house, a country, a planet). This sense of scale goes far beyond Montello's (1993) four-level classification to encompass scales beyond the range of ordinary human experience. In such cases, the distances between entities can either be condensed or expanded. If condensed, large distances can be treated as the internal relations that define an object. Thus, geographers might imagine holding the world in a hand, or astrophysicists might be able to look down on a galaxy and see it at a single glance. Vice versa, in thinking about the structure of a molecule, or at a somewhat larger scale, the structure of the heart or the brain, very small distances can be mentally expanded to the point where the relations among components becomes similar to the relations among mountains, churches, and other landmarks. Thus, surgeons can imagine themselves traveling around or through the human heart, or chemists can imagine themselves walking around a molecule. Understanding of science commonly requires dealing with such scales, in time as well as in space. Thus, scaling at extreme ranges is a barrier to science learning, albeit one that can be overcome (Resnick, Davatzes, Newcombe, & Shipley, in press; Resnick, Newcombe, & Shipley, in press).

SPATIALIZING AS A SYMBOLIC TOOL

There are also abstract symbolic means for spatial representations of both the kinds we have been discussing. For example, for intrinsic information, we can make a diagram of neural structures, for extrinsic information, we can make a subway map. We can also represent nonspatial information spatially, as in the periodic table, or in a cladogram based on Linnaean classification. We can certainly talk about space, and often do. While the extent to which spatial language restructures spatial thought is hotly debated (e.g., Gleitman & Papafragou, 2013; Majid, Bowerman, Kita, Haun, & Levinson, 2004), no one doubts that spatial language exists, or that it is widely used metaphorically, arguably more than any other source domain (Lakoff & Johnson, 2008). Furthermore, analogical thinking, the core of intelligence in the model shown in Figure 15.1, is a mapping of one domain onto another, with the structure-mapping model a predominant theoretical account (Falkenhainer, Forbus, & Gentner, 1989). Maps restructure thought (Uttal, 2000), and sketching is an active tool for thought (Forbus et al., 2011), as are spatial gestures in nonspatial as well as spatial domains (Beaudoin-Ryan & Goldin-Meadow, 2014; Goldin-Meadow, 2015). Mental imagery is used not only for imagining life on vacation or a delicious meal, but also to solve problems and make inferences (Huttenlocher, Higgins, & Clark, 1971). Each of these tools vastly increases the range and power of the human mind, in STEM and beyond, to areas as diverse as equipment design, political campaigning, and epidemiology. Sadly, because the focus of the chapter has been on distinguishing navigation and object manipulation, we can only scratch the surface of presenting the large amount of knowledge on these symbolic spatial tools, giving some brief indications of the health of this very active area of research.

Let's start with analogy, recalling its centrality to human intelligence as shown in Figure 15.1. Any analogy is spatial in an abstract sense, because it involves a mapping between entities and attributes in one domain to entities and attributes in another. Analogies are useful in reasoning, not only because they highlight similarities but also because they highlight differences, and they are known to be useful in learning (Alfieri, Nokes-Malach, & Schunn, 2013; Goldwater & Schalk, 2016). Science instruction often uses analogy, as when the atom is compared to the solar system, or as when students are asked to understand the geologic timescale by analogy to the human life span. Mathematics instruction can also usefully involve analogy, especially when two problems are simultaneously visible and explicitly compared (Begolli & Richland, 2016). We are getting an increasingly good idea of when and how and why analogies work in the elementary classroom (Richland & Simms, 2015; Vendetti, Matlen, Richland, & Bunge, 2015), in children's museums (Gentner et al., 2015) and for university students (Jee et al., 2013; Kurtz & Gentner, 2013), as well as some idea of the neural underpinnings of analogical reasoning (Vendetti et al., 2015). Basic behavioral research continues on children (Shayan, Ozturk, Bowerman, & Majid, 2014) and adults (Goldwater & Gentner, 2015).

Spatial language is very intertwined with the development of spatial thinking. For example, we know that children's spatial intelligence benefits from early learning of spatial language, and boys hear more spatial language from adults than girls (Pruden, Levine, & Huttenlocher, 2011). Furthermore, learning specific spatial words can have specific cognitive advantages. For example, word-learning biases can be harnessed to help children learn difficult spatial mathematical concepts, such as understanding angle size (Gibson, Congdon, & Levine, 2015).

Maps and diagrams play a ubiquitous role in science instruction and in scientific reasoning. Students need to be taught how to read them, and how to coordinate reading of text and diagrams (Bergey, Cromley, & Newcombe, 2015; Cromley et al., 2013). Areas of active investigation include when static representations are sufficient and when dynamic representations add value, and for whom (Sanchez & Wiley, 2014), and how to specify better when and how to introduce these symbols (Uttal & Sheehan, 2014; Uttal & Yuan, 2014). Furthermore, sketching (or the creation of diagrams or maps by the learner) seems likely to be especially helpful (Gagnier, Atit, Ormand, & Shipley, in press; Sung, Shih, & Chang, 2015). Additionally, the nature of student sketches is diagnostic of their conceptual understanding (Jee et al., 2014), and sketching is thus likely to be helpful as a formative assessment in the classroom.

Physical experience of relevant scientific concepts engages the motor system in learning, a theme that emerged in research on mental rotation. It has been found to work for concepts such as angular momentum (Kontra, Lyons, Fischer, & Beilock, 2015). However, not all scientific concepts can be directly experienced, and even for those concepts that can be, science eventually requires abstraction for generality. Learning may occur on an action-to-abstraction continuum (Goldin-Meadow, 2014, 2015), with gesture pushing the learner along this continuum. Gesture can express spatial relations at least as well as language—better in some ways because several relations can more easily be expressed, in an analogue fashion rather than categorically. The motor system is involved in understanding others' gestures (Ping, Beilock, & Goldin-Meadow, 2014) and gesture can work better than action, even action that is accompanied by words (Trofatter, Kontra, Beilock, & Goldin-Meadow, 2014).

CONCLUSION

If we now have an idea of natural kinds of human thinking in the spatial world, we have a foundation that can allow us to accelerate progress in delineating development, neural substrates, variability, malleability, and real-world impact of these important cognitive skills. There are multiple questions in this increasingly active and interdisciplinary area. Answering them will require collaboration across a variety of research traditions in psychology, ranging from testing to cognition to development to cognitive neuroscience, and including considerations of personality and social psychology that we have hardly touched on. The enterprise will also require expertise from linguistics, geography, and geographic information science, artificial intelligence and robotics, cellular and systems neuroscience, and STEM education. It is an exciting time.

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