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Spatial Development

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Abstract and Keywords

This chapter is a selective review of spatial development, stressing several points. First, we suggest that spatial development can be usefully considered to have two strands: (a) the development of intraobject (or intrinsic) representations along with the ability to transform them (e.g., in mental rotation) and (b) the development of interobject (or extrinsic) representations and the ability to use them to navigate. Second, we argue that both lines of development begin from strong starting points, but also undergo considerable development. They are far from innately specified, nor do they have a modular architecture. Third, we discuss the amplification of spatial skills by human symbolic capabilities, including language, use of maps and models, and gesture. Fourth, we identify areas where research is lacking, most notably the formal description of intraobject skills and the charting of their normative development, the exploration of the sources of individual differences in navigation-relevant skills, and the applications of research to education.

Keywords: spatial development, spatial cognition, spatial ability, navigation, mental rotation, spatial language, maps, gesture, neoconstructivism

Key Points

1. Understanding spatial development is important because spatial skills are a central aspect of evolutionary adaptation and a key component of human intellect; furthermore, they have practical significance, both in everyday life and in facilitating the learning of science, technology, engineering, and mathematics.
2. Spatial development can be usefully considered to have two strands: (a) the development of intraobject (or intrinsic) representations along with the ability to transform them (e.g., in mental rotation) and (b) the development of interobject (or extrinsic) representations and the ability to use them to navigate.
3. The ability to represent and transform the external world to allow successful navigation requires the coordination of egocentric and allocentric modes.
4. Spatial development in both intrinsic and extrinsic strands begins from strong starting points but also undergoes considerable development; representations of the internal structure of objects and their positions in the wider world are far from innately specified, nor do they have a modular architecture.
5. There are reasons to think that initial representations of spatial and quantitative extent are intertwined, and they must be differentiated during development.
6. Spatial skills are augmented by human symbolic capabilities, including language, use of maps and models, and gesture.
7. Development of symbolic understanding is a gradual and complex process involving (p. 565) the development of several skills: the ability to understand the representational nature of spatial symbols and the spatial correspondences between symbols and their referents.
8. Maps allow for the visual communication of spatial information, which may, in turn, help children develop the ability to represent and communicate spatial relations among locations.

9. Although fleeting, gestures can greatly enhance spatial communication by providing visual information, similarly to maps.
10. A combination of formal and informal spatial learning can foster the required suite of skills for children to succeed in everyday spatial tasks, as well as garner interest and success in the STEM disciplines.

Babies are born with limited abilities to move around the world or to manipulate objects in it. They wave their arms and legs, and they curl their hands into fists when their palms are touched. But they cannot find their way anywhere, or use any of the astonishing number of tools invented by their forebears. How does this situation change? How do infants become adults who can navigate through unfamiliar territory and who can not only use but invent tools? Why will some infants become adults who are exceptionally skilled at these activities, while other infants will grow into the sort of adults who constantly get lost, or who put together a bookshelf backwards—the kind of people who refer to themselves deprecatingly as "not good with maps" or "not a do-it-yourself person"? And how can we maximize the spatial skills of the population to help meet the demands of a technological society, both for people who are fascinated by spatial challenges and wish to augment their abilities, and for those who are the future klutzes?

These seemingly simple questions disguise a territory of much greater complexity, characterized by substantial disagreement and fractionation. To take outright disagreement first, considerable debate has centered on the nature of normative development. Do infants develop into competent adults in a protracted course of development propelled by interactions with the physical environment (as Piaget thought)? Or do they develop due to social interactions, linguistic input, and apprenticeship in the use of cultural tools such as maps or the use of star systems (as Vygotsky thought)? Or are they actually equipped from the beginning with core knowledge of objects and space, later augmented by the acquisition of human language (as argued in the past few decades by Spelke)? The long history of arguments on these theoretical issues has been reviewed by Newcombe and Huttenlocher (2000, 2006; see also Newcombe, 2002a). Newcombe and Huttenlocher have proposed an overarching perspective on spatial development called *adaptive combination* theory that unites the important insights of constructivism, Vygotskyanism, and nativism, while discarding some of the least tenable propositions of each. In terms of developmental theory, the adaptive combination framework is an example of *neoconstructivism* (see chapters in Johnson, 2009b and in Woodward & Needham, 2009; Newcombe, 2002b, 2010). In terms of spatial cognition, the adaptive combination framework is an example of *Bayesian* theories (see Cheng, Shettleworth, Huttenlocher, & Rieser, 2007). One purpose of this chapter is to offer an overview of issues involved with how to characterize the typical course of spatial development. Because the Piagetian and Vygotskyan frameworks have been previously reviewed in some detail (Newcombe & Huttenlocher, 2000), we focus on why adaptive combination is to be preferred to a core-knowledge approach.

Disagreement can be distressing, but fractionation (lack of any talk at all as opposed to disagreement and heated debate) is arguably worse. Lack of engagement ensures a lack of progress. Such lapses in communication have been seen in the field of spatial development in several ways. First, there is a gulf dividing researchers interested in normative development from researchers interested in individual differences. These researchers work in communities that do not speak much to each other and that use different methods and statistical techniques—experiments and analysis of variance in the study of normative development, and psychometric tests and correlational techniques in the study of individual differences. The two research communities even concentrate on different aspects of spatial cognition. Newcombe (2002a) divided her review of spatial cognition into two main areas, *navigation* and *mental rotation*. The study of normative development has concentrated largely on navigation (with some exceptions), beginning in infancy with the study of search for objects hidden in the environment. In contrast, the study of individual differences (again with some exceptions) has largely focused on mental rotation and other skills that center on mental manipulation of objects. However, more than 50 years after Lee Cronbach called for uniting the "two disciplines of scientific psychology" (Cronbach, 1957), we have started to see significant progress in integrating the study of normative development with the study of the development of individual differences.

(p. 566) There is a second fractionation, stemming in part from the difficulties in connecting research on normative functioning with research on individual differences. Lack of a coordinated approach has limited the ability of research on spatial development to contribute to the solution of applied and educational issues, notably how to foster the development of the spatial skill increasingly required in a complex technological society. However, again there is the beginning of good news. More than 40 years after George Miller issued his call to "give

psychology away" (Miller, 1969), we have started to see significant attention to using our understanding of spatial development to help people realize their full potential in spatial tasks (Kastens et al., 2009; Liben, 2006; National Research Council, 2006).

A third fractionation involves a splintering rather than a gulf. A gulf divides two sides—making halves. Splintering causes multiple islands, making fractions smaller than halves. Research in spatial development has often proceeded with insufficient attention to research in areas that are close to it—spatial functioning in adults is one example, the decline of spatial functioning in the elderly is another example, the development and use of spatial language is yet another. In addition, there is significant research on spatial cognition in nonhuman animals (comparative research); neuroscience on a variety of levels with a variety of techniques used with a variety of species; computer science and artificial intelligence (e.g., the task of programming a robot that can navigate on its own has proved to be a formidable but interesting challenge); geography and the other spatial sciences. Each of these fields has something to contribute to the overall puzzle, but evolving on separate islands, the fields have (like Darwin's finches) developed differently, with nomenclatures that are not mutually intelligible and other barriers to interdisciplinary dialog. This chapter cannot take on the task of a full interdisciplinary survey; we refer readers to Nadel and Waller's (in press) edited volume for reviews that can help developmental researchers to use insights from comparative research, computer science, and neuroscientific investigation as needed to illuminate normative development, understand individual differences, and have translational impact.

This chapter begins with placing spatial cognition in a context that makes clear why we should care about it ("The Whys and Wherefores of Spatial Development"). In this section, we introduce the distinction between two subdomains of spatial skill: skills related to navigation (where are objects in relation to each other) and skills related to tool making (representing individual objects and ways to transform them). In the second section ("The Whats of Spatial Development"), we expand on the typology offered in the first section, also touching on issues that relate to the study of individual differences and our ability to assess them. We next offer an overview of the recent study of spatial development ("The Nature of Normative Development in Early Spatial Behavior"), concentrating on the contrast between the Spelke and Kinzler (2007) core knowledge perspective and the view of spatial development advanced by Newcombe and Huttenlocher (2000, 2006; see also Newcombe, 2002a). The relevant literature for this section largely centers on infancy and early childhood and mostly concerns behavior in small-scale spaces that are directly experienced rather than presented symbolically using maps or spatial language. When we turn to examine the development of symbolic means of spatial representation ("Spatial Symbols and Spatial Development"), we switch attention in doing so to older children and to larger-scale spaces. This section covers the use of spatial language, the use of maps and models, and the use of gesture in reasoning about space. In our last section, we turn attention briefly to how to use what we know about spatial development to have translational impact on increasing spatial skills, and on reducing sex and socioeconomic status (SES) differences in spatial skills ("How to Use What We Know").

The Whys and Wherefores of Spatial Development

There are many reasons to be interested in spatial development. First, human spatial cognition plays a central role in our species' evolution, adaptation, and current everyday functioning. Second, spatial skills are a key component of human intellect, and hence need to be incorporated in any successful model of the architecture of the human mind. Third, there is growing evidence that spatial skills are specifically relevant to success in science, technology, engineering, and mathematics (STEM) disciplines.

Two Kinds of Spatial Skill and Their Evolutionary Significances

There are two spatial challenges faced by our species. The first challenge is widely shared across the animal kingdom: How can we move successfully around the world? The second challenge is a more species-specific one: How can we manipulate (p. 567) objects in our world to make and use the tools that constitute such a vital part of our adaptive specialization?

Navigation

Being able to move around the world allows mobile animals to search for food, water, and mates. But mobility

comes with a price tag—animals that move need to keep track of where they are and must be able to return to a home base, to rejoin conspecifics, and to avoid danger. Different species solve these problems in different ways, depending on their environmental affordances and adaptive pressures. Survey knowledge is easier to obtain for animals that fly, chemical gradients may be more vital underwater, a magnetic sense may be especially crucial for migratory species, and so on. Humans do not fly, lack keen chemical senses, and are not able to sense the earth's magnetic field. Indeed, in unfamiliar environments when the sun is not shining, humans are prone to walking in circles (Souman, Frissen, Sreenivasa, & Ernst, 2009). However, our abilities to represent the spatial environment and to navigate in it are luckily strengthened by the symbolic ability in which we excel. We can draw maps, describe space in language, and invent systems of navigation using the stars, or technology such as the compass, the astrolabe, and (now) the GPS. One of the fascinating aspects of research in spatial cognition is the opportunity to put human navigation in cross-species perspective (see Jacobs & Schenk, 2003; Shettleworth, 2009). Navigation depends on the representation of the position of objects and environmental features with respect to each other, and the positioning of a moving self within this landscape. The same representations allow us to find hidden objects.

Tool Making

Another kind of spatial challenge involves the representation of the shape and internal structure of objects (considered independently of their position with respect to other objects or a frame of reference) and the ability to transform that representation by imagining the object's structure being rotated, sliced through, or changed by folding, melting, or the application of a force (e.g., hammering). These kinds of spatial skill are the ones mostly assessed by psychometric tests. Skills of this kind appear to be typical of humans but seem not to be widely shared among other species, including nonhuman primates (Burmann, Dehnhardt, & Mauck, 2005; Köhler, Hoffmann, Dehnhardt, & Mauck, 2005; Okamoto-Barth & Call, 2008). The ability to transform the internal structure of objects may, in fact, underlie the human capacity for tool making, an adaptive characteristic that is distinctive to our species (Baber, 2003), even though some other species may share it (e.g., there are reports of tool use in crows; Kenward, Weir, Rutz, & Kacelnik, 2005).

Navigation and Tool Use in the Modern World

These two abilities—the ability to represent and transform the environmental landscape and the ability to represent and transform internal object structure—both have adaptive significance. But they are not just relics of an evolutionary past. Even with GPS, humans are challenged to find their way around novel environments as they travel and explore. And we still need to put together furniture ("some assembly required") and puzzle out how best to pack things into defined spaces. Interestingly, some of us even do these activities for pleasure—orienteering, road rallies, and geocaching test our navigational skills, while jigsaw puzzles and Rubik's cubes challenge our ability to transform object structure.

Spatial Skill in the Structure of Human Intellect

A second reason to be interested in spatial development is that spatial functioning seems to form a vital part of the structure of human intellect. Three examples drawn from different research traditions illustrate this point: decades of factor-analytic research showed that visualization is a well-defined component skill within general intelligence (Carroll, 1993); spatial intelligence was one of the types of intelligence proposed in multiple-intelligence theory (Gardner, 1983); and approaches to working memory have distinguished between verbal working memory and the visuospatial sketchpad (Baddeley, 1986). There is controversy about some of these matters: for example, see McGrew (2009) for an update on developments in the psychometric approach to the structure of intellect; Waterhouse (2006) for a critique of the theory of multiple intelligences; and Kane, Hambrick, Tuholski, Payne, Engle, and Wilhelm (2004) for evidence that domain-specificity may characterize short-term memory but not working memory. Nevertheless, although we have yet to define the architecture of the human mind/brain, there is strong reason to believe that spatial functioning will be a relevant element in this architecture.

(p. 568) The Practical Significance of Spatial Skill

A third reason to be interested in spatial development is that, on the practical and policy side, spatial ability appears to be relevant to people's interest in STEM, and their ability to succeed in STEM disciplines. Many short-

term correlational studies have demonstrated these kinds of correlations, but often without excluding reverse causality (taking science courses improves spatial ability) or third-variable causation (people who are generally smart are also good at spatial tests, and smart people often like science and math). Recently, however, analyses of large longitudinal data sets have shown that spatial ability predicts choice of STEM majors and careers, even after controlling for important third variables such as verbal and mathematical ability, and even when spatial ability is measured in early adolescence while the STEM outcomes occur decades later (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009; Webb, Lubinski, & Benbow, 2007). In analyses of Project Talent data (the same data set analyzed by Wai et al., 2009), Hedges and Chung have even shown these effects after controlling for interest in STEM subjects in high school, thus strongly implicating a causal connection between spatial ability and STEM careers (Hedges, personal communication).

Additionally to these analyses of large data sets, there are well-controlled correlational studies that indicate a relation of spatial ability to success in training for specific careers that seem to demand spatial reasoning, such as dentistry (Hegarty, Keehner, Khooshabeh, & Montello, 2009), surgery (Wanzel et al., 2002), and other disciplines (see Hegarty & Waller, 2005). We also know from recent fine-grained studies of physics problem solving that spatial visualization is related to better ability to interpret graphs and solve problems in kinematics (Kozhevnikov, Motes, & Hegarty, 2007). Furthermore, intervention to increase spatial skill in prospective engineering majors who test relatively low as they enter the major increases chances of completing an engineering degree (Sorby, 2009). Thus, overall, we have good reason to believe that spatial ability is causally relevant to STEM interest and success. Because efforts to improve spatial ability are known to be successful (see meta-analyses by Baenninger & Newcombe, 1989; Uttal et al., 2012), we also have good reason to be optimistic about our ability to increase interest in STEM disciplines and people's ability to succeed in mathematics, science and engineering.[1]

An important unanswered question is whether the spatial representations and abilities that support navigation are related to STEM interest and achievement. To date, only within-object spatial encoding and transformation (e.g., mental rotation) have been assessed in relation to STEM. We know virtually nothing about whether the ability to represent the environment and navigate within it is related to STEM. This gap in our knowledge is difficult to solve as of yet, because we lack a good way to assess individual differences in between-object representations and transformations. We need a testing method that is short enough and inexpensive enough to use in longitudinal studies with large samples.

Section Summary

Spatial development is of interest for evolutionary, theoretical, and applied reasons. From an evolutionary point of view, we suggest that there are two distinct sets of spatial skills: interobject representations and processes relevant to navigation, and intraobject representations and processes relevant to tool making. Both kinds of spatial skill remain relevant today, and intraobject spatial skills are known to relate longitudinally to success in the STEM disciplines. A successful account of human intellect and its development must take spatial functioning into account.

The Whats of Spatial Development

We have made the case that spatial development is interesting from both a theoretical and a practical point of view. But what is spatial development the development of? We have distinguished navigation and tool making as functions with adaptive value. In doing so, we focus attention on the distinction between representations of relations among environmental features (as required for navigation) and representations of within-object structure (as required for tool making). Understanding the "whats" of spatial development requires distinguishing between these two kinds of reasoning. We begin with some empirical reasons to differentiate them, then consider the relation of this typology to prior efforts to subdivide the spatial realm, and finally delve a bit deeper into analyses of the various kinds of representation that support navigation in particular.

Why Two Lines of Development?

There are a variety of reasons for dividing spatial skill into two spheres; see Chatterjee (2008) (p. 569) for a fuller discussion. For now, let us simply consider research that shows, surprisingly, that perspective taking (a task on the navigation side) and mental rotation (a task on the tool-making side) behave quite differently from one another in

several ways, even though they could be regarded as formally equivalent—one task could be turned into the other one with ease by a computer programmer. However, it has been repeatedly found that the two tasks are influenced by different factors: in some circumstances one task is more difficult, and in other circumstances the other task is more difficult (Creem, Wraga, & Profitt, 2001; Huttenlocher & Presson, 1973, 1979; Simons & Wang, 1998; Wraga, Creem, & Profitt, 2000; Wraga, Creem-Regehr, & Profitt, 2004). Furthermore, analyses of individual differences show that people who are good at mental rotation are not necessarily good at perspective taking, and vice versa (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). In fact, mental-rotation and perspective-taking tasks turn out to have different neural bases (Wraga, Shephard, Church, Kosslyn, & Inati, 2005); neuroscientific investigation suggests that interobject and intraobject representations and transformations are generally supported by very different brain areas, as are the terms in spatial language that relate to those representations and transformations (Chatterjee, 2008). Importantly from the point of view of the tool-making function, mental rotation is frequently (although not always) found to involve activation of motor areas relevant to the hands (Wraga, Thompson, Alpert, & Kosslyn, 2003).

Distinguishing between within-object encoding and transformation and between-object encoding and transformation raises an important issue: are abilities in the two subdomains different enough that calling them both "spatial" becomes confusing? In fact, there are at best modest correlations between psychometric tests of spatial ability, which focus on within-object skills, and learning of large-scale space, which focuses on between-object skills (Hegarty, Montello, Richardson, Lovelace, & Ishikawa, 2006; Sholl, 1988). Although future research is needed, at present it seems fair to say that there may be two distinct classes of skill, no more correlated than any cognitive skills are with each other. They are both "spatial" in a formal sense, because both involve representations and transformations of three-dimensional information, but they are functionally distinct.

Prior Efforts to Characterize Spatial Skill

There have, of course, been many prior efforts to categorize and structure spatial abilities. How does our proposal of an important distinction contrasting within-object and between-object encoding and transformation relate to those efforts? Hegarty and Waller (2005) provide a thorough and reflective review of the history of classificatory efforts in the spatial domain, beginning with the factor-analytic tradition and proceeding through more recent cognitive analyses of tests devised by psychometricians. They reach several conclusions. First, they argue that success on spatial tasks is powerfully influenced by nonspatial factors such as strategies and executive-processing capacity, noting that research on such general or central factors has often proceeded in isolation from research on spatial skill. We agree. The implication is that knowledge of such factors needs to be integrated with research on spatial functioning to create a full understanding. Second, they believe that a bottom-up approach to classification is unlikely to work; there is a need for a theoretical framework that can organize analysis of the organization of spatial functioning. We agree, and put forward the interobject and intraobject distinction as a step in this direction. Third, although the classification efforts they reviewed mainly focused on intraobject encoding and transformation, they also review data on individual differences in navigation abilities and interobject representations, with the aim of galvanizing attention to assessment in that area and consideration of how skills in it relate to skills of the sort more traditionally assessed by psychometric tests. We could not agree more that assessments of these skills are urgently needed.

Characterizing Navigation

Looking more closely at between-object encoding and transformation, there have been robust efforts to characterize the nature of navigation in the large-scale environment. While this effort has not concerned itself much with individual differences, it has been quite successful in developing a characterization of this domain. There is now widespread agreement that there are two main ways to function in the larger-scale world (Gallistel, 1990; Newcombe & Huttenlocher, 2000). One method involves encoding of self movements and updating of relations of the self to other objects on the basis of those movements, and has been called *dead reckoning* or *inertial navigation.* (This system is akin to *egocentric responding* in the developmental literature, although egocentrism involves a failure of updating, (p. 570) and akin to *response learning* in the animal cognition literature.) The second system involves encoding of object-to-object relations, with some of these objects being landmarks and organized as a frame of reference. This method has been called *allocentric coding*, or *place learning* in the animal cognition literature, with a more controversial term with added meaning being *cognitive map*.

Allocentric coding may involve more than landmarks and frames of reference: Jacobs and Schenk (2003) have drawn attention to the importance of gradients, such as olfactory gradients in water that seem important to aquatic animals, or such as the slope of the ground, which can be a powerful cue (Nardi & Bingman, 2009). Theoretical advances in the analysis of large-scale space have occurred over recent decades due to extensive comparative work, careful cognitive analyses, developmental investigation, and neuroscientific research (Doeller, King, & Burgess, 2008; Epstein, 2008).

Not everything is settled in terms of how to characterize environmental representations. Controversies remain, including whether there is such a thing as a cognitive map (see Shettleworth, 2010, for a cogent comparative analysis), whether there is a separate geometric module that guides reorientation (see Cheng, 2008, for a recent analysis and proposal of a local-view alternative, and Twyman & Newcombe, 2010, for a similar analysis and a review of various alternatives), and most importantly for developmentalists, what the origins of these competencies are. Nevertheless, it is striking that we have excellent theory and typology for large-scale space (and hence for the functions of navigation and object search) and yet lack well-developed assessment instruments and databases on individual differences in this area.

Section Summary

Prior attempts to characterize the nature of spatial skills have been disappointing. We have argued for a typology that distinguishes sharply between interobject and intraobject representations and processes, on behavioral, linguistic, functional, and neurological grounds. What we know about these two kinds of spatial skills is different in each subdomain. Knowledge about interobject cognition, used for navigation, has a strong theoretical basis, and much is known about its development. However, research in this area has largely neglected the analysis of individual differences and their development, in part because of a lack of assessment instruments. Knowledge about intraobject spatial cognition, used for tool making, has a much richer tradition of assessment of individual differences. However, there is a marked focus on just one kind of transformation, namely mental rotation, and a relative lack of research of knowledge about other kinds of transformation, such as folding, cross-sectioning, or plastic deformations. One reason for this situation is that there has been less formal theorizing than has been true for navigation about the nature of the overall challenge—for instance, there is no formal typology of the variety of intraobject transformations possible.

The Nature of Normative Development in Early Spatial Behavior

Piaget deserves credit for identifying the key questions about spatial development in the first few years of life, including how infants come to understand what constitutes an object, and how to remember where objects are. In pursuit of the answers, he also identified striking phenomena, including the A-not-B error, and the egocentric-to-allocentric shift. Research on these questions and phenomena has been intense and has been augmented by investigation of other phenomena, including the development of place learning, and whether or not there is a "geometric module" that guides reorientation. Along the way, various other theories have come into play to explain spatial development, including versions of nativism, connectionism, and dynamic systems theory. The literature on each topic has now grown to the point where a single overview chapter cannot do justice to it all. For expanded discussion of specific issues, see Newcombe and Huttenlocher (2000, 2006) on the A-not-B error considered from the point of view of what it tells us about spatial development, and on the egocentric-to-allocentric shift; Atkinson and Nardini (2008) on spatial vision and its development, especially in infancy; Learmonth and Newcombe (2010) on place learning in comparative perspective; chapters in Plumert and Spencer (2007) for particular contemporary points of view; and recent reviews by Vasilyeva and Lourenco (2010) and Holden and Newcombe (in press) that give an overview of many of the issues with an emphasis on an adaptive combination approach to the development of spatial memory.

Rather than offering an in-depth literature review, the aim of this section is to contrast the core knowledge and the neoconstructivist approaches to spatial development. A recent presentation of the core-knowledge perspective proposes four (and maybe five) separable systems of core knowledge (p. 571) (Spelke & Kinzler, 2007). Two of these systems are directly relevant to spatial development: object representation, and geometric relations in the environment. Strikingly, these systems correspond fairly well to our proposed distinction between intraobject and interobject encoding and transformation—intraobject cognition corresponds roughly to the proposed core-

knowledge systems of object representation and interobject cognition corresponds roughly to the proposed core-knowledge system of geometric relations in the environment.[2] In addition, a third proposed system of core knowledge, the core number system, may be relevant to spatial development. That is because there has been debate regarding whether number understanding is autonomous from spatial thinking from the start, as proposed by Spelke and Kinzler, or is initially related to spatial thinking, with both numerical and spatial systems beginning as forms of an overall quantitative thinking system (Mix, Huttenlocher, & Levine, 2002; Newcombe, 2002). Let us examine each of these three systems in turn.

Object Representations

Piaget proposed that infants construct their knowledge of objects as connected entities with continuing existence in specifiable spatial locations through visual and manual exploration extending over the first 18 months of life. This picture of development came into question in the 1980s, however, with Kellman and Spelke's (1983) demonstration that 3- to 4-month-old infants use the Gestalt principle of common fate to group their perceptual world into objects, and with Baillargeon, Spelke, and Wasserman's (1985) demonstration that 5-month-old infants expect that objects continue to exist even when hidden, and that they apparently represent the objects' solidity and height. Spelke and Kinzler (2007) review evidence indicating the existence of a core system of object representation that centers on cohesion (i.e., objects move together as wholes), continuity (i.e., objects move on connected paths without obstructions), and contact (i.e., objects do not interact at a distance). In addition, they point to evidence that the proposed system has a signature limit of four objects, is present at birth and continues through life, and is shared with nonhuman primates.

Questions About a Core System of Object Representations

There are several reasons to be cautious about a strongly nativist interpretation of demonstrations of very early infant competence in this domain. Early qualms were voiced by Haith (1998), but considerable further evidence has accumulated since that time. First, Scott Johnson's programmatic research has shown that visual learning can explain the development of the principles of object cohesion and continuity over the first few months of life (Johnson, 2009a, and Johnson's chapter in this handbook). An infant with normal vision and known learning mechanisms, living in an expectable world in which solid objects obey physical laws, will be guaranteed to develop these principles through experience. Second, Amy Needham has conducted a series of studies showing that infants' manual exploration of objects is vital in their learning about the nature of objects, including where objects are demarcated (Needham, 2009). An infant with normally developing manual skills and known learning mechanisms will be guaranteed to further develop object principles constructed in the first few months by vision alone. Third, Rachel Keen has shown that toddlers do not apply principles of continuity and solidity in an action task, raising questions about the nature of the representations that support findings with infants using looking-time methodology (Keen, 2003). Keen's findings are consistent with the notion of graded representations used in connectionist models of the development of understanding of objects (Munakata, McClelland, Johnson, & Siegler, 1997). Overall, what emerges from these three lines of research is support for the idea that a system of object representation is constructed in the first year of life by visual and manual exploration.

This way of thinking is broadly consistent with constructivism, although it is different in many important ways from Piaget's original thinking. It posits stronger starting points (far from a blank slate, not at all traditional empiricism or even traditional constructivism) and much faster progress than Piaget thought he saw. In addition, contemporary research methods allow us to conduct a more careful analysis of mechanisms of development than Piaget was able to do, augmented with computational models. In short, this way of thinking is *neoconstructivism*.

Neoconstructivist thinking is further supported by a line of research growing from Xu and Carey's (1996) finding that infants rely exclusively on spatiotemporal principles in determining the presence and number of objects in the world. Babies less than 12 months in their studies seemed to believe that there were two objects rather than one object behind a screen when each of two perceptually (p. 572) and conceptually distinct objects appeared in regular oscillation (see also Newcombe, Huttenlocher, & Learmonth, 1999; Xu, Carey, & Quint, 2004). Fundamental changes in how babies compute the number of objects present in a scene fit poorly with a core-knowledge position. The Xu and Carey findings do, however, pose the puzzle of how to reconcile them with data showing that perceptual information does serve to differentiate objects from each other for much younger infants (Needham & Baillargeon, 2000). One possibility is that the Xu–Carey paradigm is simply too challenging to allow younger infants

to demonstrate their true competence, and there is support for this position (Wilcox & Baillargeon, 1998; see also Krøjgaard, 2007, and Xu & Baker, 2005). Subsequent research has also shown that very salient featural information can serve to differentiate and enumerate objects in infants younger than 12 months (e.g., in a comparison of a humanlike object to a nonhuman one; Bonatti, Frot, Zangler, & Mehler, 2002). Nevertheless, spatiotemporal information usually is dominant (Krøjgaard, 2007; Xu & Baker, 2005). Most important in resolving this puzzle has been Teresa Wilcox's careful program of research on infants' use of various perceptual characteristics of objects, including color, pattern, luminance, and auditory characteristics. Wilcox has shown that there are varying ages at which infants can use each attribute to delineate objects in varying circumstances. Most intriguingly, she has shown the effect of experience on the use and weighting of these various characteristics (Wilcox & Woods, 2009).

Thus, overall, the evidence suggests that the factors that delineate objects are constructed by infants in the course of interaction with an expectable world, in accord with principles of an adaptive combination approach (and, possibly, a Bayesian approach, although the quantitative evaluation necessary to establish Bayesianism has not yet been conducted).

Mental Rotation

The core-knowledge approach concentrates on the definition of objects rather than on the coding of their internal structure and the transformation of that coding in operations such as rotation or folding. In this regard, the core-knowledge approach differs substantially from our proposed typology by ignoring an account of functionally important characteristics of objects. Piaget had of course dealt with mental rotation, although interestingly not in the same works in which he addressed spatial development but rather in his book on mental imagery. He had hypothesized that mental rotation was not possible until the age of 7 to 8 years (Piaget & Inhelder, 1966/1971). However, research by Marmor (1975, 1977) suggested a much earlier onset of mental rotation, at the age of 4 to 5 years. There was some controversy about this conclusion (reviewed in Newcombe, 2002a), but Marmor's conclusion has been widely accepted. In fact, other studies have shown some evidence of mental rotation in experiments using looking time by infants as young as 4 months (Hespos & Rochat, 1997; Rochat & Hespos, 1996), although there may be early sex differences, with male infants showing more evidence of mental rotation than female infants (Moore & Johnson, 2008; Quinn & Liben, 2008).

Despite this interesting evidence, however, the prevailing acceptance of very early mental rotation needs to be interpreted with caution. As with the object identification work already discussed, experience in viewing moving objects in the first months of life may be relevant to the demonstrated abilities, manual experience with turning objects may be relevant to continued development, and looking-time measures may not translate into the ability to act in the real world. First, mental rotation is far from fully developed in infancy. Ornkloo and von Hofsten (2007) found that it was not until 22 months that infants could mentally rotate objects to be fitted through an aperture in order to successfully fit objects through holes. Frick and Wang (2009) have shown that infants of 16 but not 14 months look longer at unexpected outcomes of mental rotation, although 14-month-olds improved after hands-on experience with a turntable. Second, mental rotation continues to strengthen through early childhood (Estes, 1998; Levine, Huttenlocher, Taylor, & Langrock, 1999; Okamoto-Barth & Call, 2008), and motor representations may be especially important for young children (Frick, Daum, Walser, & Mast, 2009; Frick, Daum, Wilson, & Wilkening, 2009; Funk, Brugger, & Wilkening, 2005). In short, mental rotation undergoes considerable development, is accelerated by motor experience, and shows important individual differences. These three facts suggest that a core knowledge of objects, even if it exists, does not provide a complete account of spatial functioning.

Environmental Representations

Just as Piaget thought that infants did not possess the concept of an object, he also thought they (p. 573) had no way to represent spatial location except in relation to the self and as at the disposal of their own actions.[3] He argued that early spatial understanding was topological, and transitioned to projective and Euclidean representations only at the age of 9 or 10 years. However, various lines of subsequent research undermined these age norms, as well as questioning Piaget's proposed typology of spatial representation. For example, the literature on perspective taking ultimately showed that egocentrism is overcome early in the preschool years (see review by Newcombe, 1989) and that even exact perspective-taking computations can be produced by children as young as 3 years, given appropriate testing (Newcombe & Huttenlocher, 1992). In addition, an egocentric-to-allocentric shift, although consistent with Piaget's formulations in a general way, occurred at younger ages and in a fashion that

showed considerable variability as a function of stimuli and testing conditions—in certain conditions, babies less than a year old showed allocentric responding (Acredolo, 1990). The outcome of this activity was generally to undermine faith in Piaget's formulations, although it has often been forgotten that, despite strong starting points and early transitions, development in spatial memory does continue through the age of 9 years or so, as Piaget proposed (e.g., Sandberg, Huttenlocher, & Newcombe, 1996).

Core Knowledge About Geometry?

Nativist approaches to environmental knowledge were relatively uncommon during the 1980s, except for Landau, Spelke, and Gleitman's (1984) claim that a blind child was able to construct Euclidean relations at ages between 2 and 4 years. This claim, however, turned out to fit poorly with the overall literature on spatial representations in the blind (Thinus-Blanc & Gaunet, 1997). The nativist approach really took on environmental knowledge in a fulsome way in its suggestion of a geometric module (beginning with Hermer & Spelke, 1994). In Spelke and Kinzler's (2007) version of a nativist approach to cognitive development, they propose that there is a core system that serves to represent "places in the spatial layout and their geometric relationships" (p. 89).

There are numerous problems with this proposal, recently reviewed by Twyman and Newcombe (2010), who organized their critique into five reasons for doubting the geometric module (summarized in Table 20.1). What approach can successfully explain all the relevant phenomena is not yet clear, but there is now an extensive knowledge base that any theory would need to encompass (summarized in Table 20.2).

Table 20.1. Five Reasons to Doubt the Existence of a Geometric Module
1. Language does not play an essential role in the integration of feature and geometric cues. **a)** Nonhuman animals are able to use geometric and feature cues. **b)** Adults' feature use is not uniquely dependent on language. **c)** 18-month-old children can integrate geometric and feature cues in large spaces.
2. A model of reorientation requires flexibility to explain variable phenomena. **a)** The relative use of geometric and feature information depends on room size. **b)** Flexibility to predict when overshadowing and blocking will or will not occur
3. Experience matters over short and long periods. **a)** Short-term training experiments demonstrate plasticity. **b)** Rearing experiments demonstrate plasticity.
4. Features are used for reorientation: Evidence against a recent two-step model. **a)** Reorientation in an octagon **b)** Features are used as landmarks for indirect orientation.
5. Redefining the analysis of geometric information **a)** Not all kinds of geometry are used early in development. **b)** Use of scalar and nonscalar cues by toddlers **c)** Use of scalar and nonscalar cues by mice

Perhaps the most important problem, however, with the idea of a core-knowledge system for representing the spatial layout is that it is a massively incomplete account of navigation. A focus on what organisms do to recover the spatial layout once they have been disoriented ignores an essential aspect of spatial functioning and its development, namely the inertial navigation system. This system exhibits marked age-related change (Rieser & Pick, 2007) and uses Bayesian processes (Cheng et al., 2007). While in one sense disorientation is merely a methodological issue (i.e., if an experimenter does not perform disorientation, participants are able to use their

body-centered coding to recover at least a rough sense of where they are), ignoring body-centered coding can provide only a very partial view of normal navigation. In addition, we know little about development or the use of geometric information in individuals who are not disoriented; initial evidence suggests it may have an important (p. 574)

Table 20.2. Phenomena to Be Explained by Any Model of Reorientation

1. Reorientation using relative length is easier than reorientation using angle size.
2. Reorientation relies more on features and less on geometry as enclosure sizes become larger.
3. Features are more likely to be used as children get older, but the improvement is continuous in larger rooms, whereas in smaller rooms, features are not used spontaneously until 6 years of age.
4. Feature use is enhanced by language training.
5. Feature use is enhanced by prior experience with features in a variety of situations.
6. Feature use is attenuated by both language interference and spatial interference.
7. Scalar information is easier to use for reorientation than nonscalar information.
8. Overshadowing and blocking are sometimes but not always observed with featural and geometric information—and potentiation is even possible.
9. Distal feature cues are used at a younger age than proximal feature cues.
10. Movement enhances the integration of feature and geometric cues.

but as yet largely unanalyzed role in normal spatial memory (Kelly, McNamara, Bodenheimer, Rieser, & Carr, 2008).

Beyond Core Knowledge of Geometry to an Adaptive Combination Approach

As just argued, a central problem with a core-knowledge approach to environmental representations is that it simply ignores most of the relevant data and phenomena in the area. There is much more to navigation than reorientation, including inertial navigation as just mentioned, and the use of symbolic representations, as discussed in the next major section. In addition, there is a wealth of information on topics such as the use of strategies in navigation (see Newcombe & Huttenlocher, 2000, for review), the use of categories in spatial memory (see Huttenlocher & Lourenco, 2007, and Plumert, Hund, & Recker, 2007, for review), and dynamic change in spatial location memory (Spencer & Hund, 2002; Spencer, Smith, & Thelen, 2001). One of the clearest ways to see how much the core-knowledge perspective omits is to examine recent papers by Marko Nardini and his collaborators (Bullens, Nardini, Doeller, Braddick, Postma, & Burgess, 2010; Nardini, Burgess, Breckenridge, & Atkinson, 2006; Nardini, Jones, Bedford, & Braddick, 2008; Nardini, Thomas, Knowland, Braddick, & Atkinson, 2009). In these papers, there are important demonstrations of how use of various frames of reference changes with age. For example, Nardini and colleagues (2008) found that children as old as 8 years fail to combine allocentric and egocentric sources of information about spatial location, alternating between the two of them in conflict situations. By contrast, adults showed evidence that they integrated cues in a Bayesian fashion, weighting them close to optimally to reduce variance. Research along these lines has high promise for leveraging our knowledge about human development across domains (Xu, 2008; Xu & Tenenbaum, 2007) and across species (Waisman & Jacobs, 2008).

Space and Number

The core-knowledge approach to number distinguishes representations of number sharply from other quantitative representations, such as representations of spatial extent, as well as of other continuous properties such as time. Spelke and Kinzler (2007) argue that the core number system is characterized by three central properties: imprecision that grows linearly with increasing values; abstract generalization across sensory modalities; and the ability to be compared and combined by addition and subtraction. Each of these ideas is somewhat controversial within the literature on number. For example, there has been debate regarding whether and how to make a sharp distinction between small and large numbers and what the nature of such a distinction is (e.g., Cordes & Brannon, 2009; Feigenson, Dehaene, & Spelke, 2004). What is more important in the present context, however, is whether or not number representations (or, at least, large-number representations) can be clearly separated from representations of other continuous quantities, especially early in development. Theorists have proposed that

number, space, and time are closely linked (e.g., Walsh, 2003). Recent evidence suggests considerable overlap of these systems, ranging from the behavioral level in infants (Lourenco & Longo, 2010) to the neural level in adults (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009). If true, the developmental challenge is to separate these systems (i.e., differentiation) rather than to link them.

Section Summary

Object representations develop over the first year of life, as infants explore the world visually and manually and gather evidence about it. The ability to imagine transformations of objects also develops, over an age range extending through (p. 575) the toddler and preschool years. Similarly, representations of the environment change in many ways over the first decade of life. An emerging perspective emphasizes the value of detailed analysis of how children learn which cues to rely on and how to weight these cues optimally. Another challenge for the future is further delineation of how the spatial and numerical systems are intertwined and differentiated.

Spatial Symbols and Spatial Development

Symbolic representations play an extremely important role in the development of spatial cognition. Perhaps the most distinguishing characteristic of human spatial cognition is that the representations and basic processes that we discussed in the prior sections are augmented through the use of symbolic representations such as spatial language, maps, models, graphs, and spatial gesture. Indeed, much of the development of spatial cognition that occurs past the preschool years is due largely to interaction with symbolic systems.

Symbolic representations of space expand what people know about spatial information and how we know it in two overlapping ways. The first is in terms of the *amount* or *quantity* of information that we can acquire. Human navigation and spatial knowledge is greatly augmented by symbolically mediated communication. Much of what we know about different spaces is *not* acquired from direct experience. For example, consider what you know about the locations of cities around the world, the borders of nations, the spatial relations between continents, etc. People must rely on the information that others can provide, either directly through conversation, pointing, etc., or indirectly, through maps, written directions that can be shared, etc. Each of these forms of spatial communication inherently involves symbolic representation.

The second influence of symbols is in terms of the *kind* or *quality* of information that symbolic representations can provide. As we will argue below, symbol systems can make available information that would be difficult or impossible to acquire from direct experience, even if one had the time and money to travel extensively. For example, it can be difficult to acquire a view of a large-scale space from a top-down view, but maps make this sort of information perceptible and therefore cognitively tractable. Likewise, the language that we use to describe spatial relations may influence what sorts of information easily comes to mind; different forms of linguistic influence may help to bring to mind alternate ways of conceptualizing spatial information. Thus, symbol systems affect not only how much we know but how we know it. In much of what follows we discuss how, when, and why the use of spatial symbols can help us to transcend the limits of our own direct experience.

We consider three spatial symbol systems: language, maps and models, and gesture. Although these three systems seem different on the surface, each can be used to convey two important types of spatial information: the structure of the space and the experience of moving through the space (e.g., giving directions). In each section, we begin by discussing the characteristics and affordances of the symbol system as it relates to the communication of spatial information. We then provide a brief overview of research on the development of the ability to understand and use the particular symbol system to acquire and to communicate spatial information.

Language

Language is obviously the most frequently used symbol system. But in contrast to maps, it is not inherently linked to spatial cognition, although it obviously can be used to describe spatial relations. What are the advantages of using language to describe space? What are the limitations?

Language and Object Representation

There is some recent evidence that language may affect the development of children's perception and conception of individual objects. Smith (2009) noted that between 18 and 24 months of age, children develop the ability to recognize geometric outlines, such as the outline of the horse shown in Figure 20.1. Before this age, children can recognize pictures of specific horses as horses, but they cannot generalize based on the shape of the generalized, geometric shape.

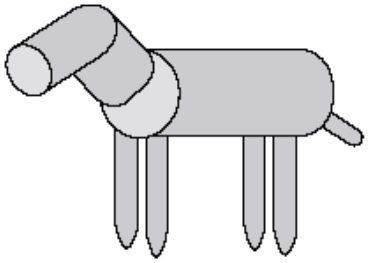


Figure 20.1 . Geometric representation of a horse. From Smith (2009).

The development of the perceptual recognition of geometric shapes may be influenced by, or at least related to, language development. Smith documented a strong correlation between children's knowledge of nouns and their recognition of geometric outlines of the referents of the nouns. For example, visual recognition of the geometric outline of a horse is correlated with knowing the word "horse." Learning the label may help children to transcend perceptual organization that is based on individual parts to one that also includes geometric shape. Of course, the direction of causality here remains an issue of controversy: Do children learn the labels or the shapes first? But in any case, (p. 576) these results demonstrate the possibility of linguistic influences on spatial perception at a young age.

Language and Spatial Relations

One of the most exciting areas of research in cognition in the past 10 to 15 years involves work on the relation between spatial language and spatial thought. Much of this debate has centered on whether, or to what extent, different linguistic expressions of space influence how we think about spatial information. Some researchers, such as Levinson (1996, 2003) have argued that different types of linguistic reference frames may influence what sorts of information people take into account when thinking about spatial location. For example, there are languages that rely on allocentric or *geocentric* reference frames to describe even simple spatial relations. Although there are many forms of allocentric reference, the common characteristic is that spatial locations are coded in terms of the surrounding environment. A common example would be to code locations in terms of cardinal directions (i.e., north, south, east, and west). In contrast, *egocentric* reference frames code locations relative to the body. A common example is left and right. Note that confusions such "my left" and "your left" can arise only in an egocentric system because each speaker habitually codes locations relevant to his or her body.

Levinson and colleagues have demonstrated cross-linguistic differences in the use of allocentric and egocentric reference frames. Western languages such as English, Dutch, German, and Spanish emphasize egocentric frameworks. Other languages, such as Tzeltal, emphasize allocentric frameworks. Large differences in memory, search, and communication have been found that are strongly correlated with the typical spatial frame of reference that one's language uses. Taken together, this line of research provides what some think is strong evidence of the influences of language on thought, and particularly spatial thought.

However, other researchers (e.g., Li & Gleitman, 2002) have strongly challenged the claim that this line of work provides evidence for strong effects of language and spatial thinking. Li and Gleitman argued that the effects of frames of reference are malleable and that language does not create or even alter a preference for a given frame of reference. Thus they reject the notion that recent work on the relation between spatial language and spatial thought is an example of a Whorfian effect—a direct and causal relation between how concepts are represented in language and how people think about these concepts.

One possible intermediate position is that spatial language can direct attention toward particular types of spatial relations, without completely constraining the possibility of representing alternative spatial relations. In

developmental work with 18-month-old infants, Casasola, Bhagwat, and Burke (2009) provide a nice example of how language can direct the acquisition of spatial concepts. They showed that brief experience with a linguistic label for "tight fit" can aid infants in forming an abstract categorical representation of this relation.

Comparative and Developmental Perspectives on the Relation Between Language and Thought

Until recently, most work on alternate spatial reference frames has focused on demonstrating their existence and investigating a variety of reference frames in different languages. Researchers now have begun to study these issues from comparative and developmental perspectives, and these studies shed substantial additional light on the mechanisms through which language might influence spatial thinking. Examples of these studies highlight the importance of symbolic influences on spatial cognition and the role of symbolic influences both in human evolution and development.

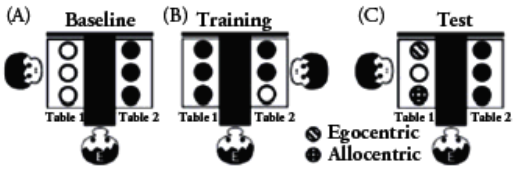


Figure 20.2 . Frames of reference task with apes. Reprinted with permission from Haun et al. (2006).

Haun and colleagues (2006) investigated the evolutionary origins of geocentric and egocentric reference frames by adapting Levinson and associates' tasks to include nonhuman apes as participants. Two orangutans and five gorillas were trained to search for food that was hidden under one of three containers, as shown in Figure 20.2. With successive search, a strong bias to search at a particular cup was induced. Then the ape was moved to the opposite side of the array. The question was whether the apes would continue to search at the (p. 577) same absolute location (and hence continue to find the hidden food despite being moved). The answer was yes; the apes chose the allocentrically correct cup significantly more often than chance and chose the egocentrically correct cup significantly less often than chance. In combination with cross-linguistic comparisons in humans, these results suggest that humans share with our evolutionary cousins an ability to code locations allocentrically. The preference for egocentric coding that seems so natural to speakers of Western languages may be the result of what Haun and colleagues called "cultural override" of our evolved preference for allocentric coding. Egocentric coding may require exposure to these terms in language; allocentric coding apparently does not and hence is available both to apes and humans.

Further evidence for the evolutionary or developmental primacy of allocentric coding comes from the work of Li and Shusterman (2007). These researchers examined specifically how and when children map spatial words to spatial frames of reference, as well as children's default assumptions as to what spatial terms might mean. Four-year-olds were taught nonsense syllables that could mean, in essence, right or left, or north and south. For example, different toys were placed at opposite ends of the room, and the children were taught that one toy was on their "Ziv" side and the another toy was on their "Kern" side. Then, the children were turned 180 degrees, new toys were placed in the room, and the children were asked to indicate which of the new toys was on the Ziv or Kern side. This manipulation can reveal how the children interpreted the nonsense words. If they took Ziv or Kern to mean north and south, then the interpretation will not be affected by the rotation, as north and south remain the same despite rotation. If, however, the children took Ziv and Kern to mean right and left, then they will point to the opposite side of the space after they are rotated.

By default, children adopted the absolute frame of reference, interpreting Ziv and Kern as meaning north and south. Thus, absolute reference frames seem to be the default assumption in young children, a finding that is consistent with Haun and colleagues' work with apes. Given that allocentric coding seems to be the evolutionary and developmental default, the reliance of many common languages on egocentric coding suggests a potential influence of language on spatial cognition and communication.

Describing Spatial Relations

One limitation of research on the relation between spatial thought and spatial language is that almost all of the studies of linguistic frames of reference have focused on the description or memory of a very limited number of

spatial relations. These studies have not addressed the development of the ability to communicate multiple locations through space, or to acquire information about multiple relations from language. In the next section we look at both the disadvantages and advantages of using language to describe more complex spatial scenes.

Describing spatial relations in words, or acquiring information about spatial relations from words, can present substantial challenges. One property of language that may pose a problem is linearity: words are given one at a time in a sequence, in accordance with the grammar of the language. Thus, only one spatial relation can be described at a time (see Newcombe & Huttenlocher, 2000). Consequently, communicating multiple locations can easily become cumbersome to the speaker and can place substantial memory demands on the listener (Brunye, Rapp, & Taylor, 2008).

One potential way of examining the communication of information about more complex spaces involves giving directions, or describing an object or scene for another person. Plumert and colleagues (e.g., Craton et al., 1990; Plumert, Ewert, & Spear, 1995, Plumert et al., 1994) investigated the development of children's comprehension of spatial descriptions. Three- and four-year-olds were asked to describe the locations of objects within a dollhouse. Even the 3-year-olds were able to describe locations in terms of a single landmark and a simple spatial relation (e.g., "the bear on the table" or "the bear next to the table"). However, only the 4-year-olds were able to use two relations to disambiguate a location. Along similar lines, Hund and Plumert (2007) and Hund and Naroleski (2008) examined how 3- and 4-year-old children (and adults) used "by" to describe proximity to a landmark, and found increases in systematicity of usage.

(p. 578) Although spatial relations in language can only be presented serially, it is possible to form a maplike mental representation from listening to a description. However, this process may require that people *integrate* the information: infer spatial relations that are not described to fill in relations. Uttal, Fisher, and Taylor (2006) investigated the development of the process of spatial integration. They asked 6-year-olds, 8-year-olds, and adults first to memorize a set of serial descriptions of a space that consisted of six rooms arranged in two rows of three. Although almost all of the children could learn the descriptions, very few of the 8-year-olds integrated the descriptions into the correct layout. When asked to construct a model of the space based solely on the descriptions they had heard, most 8-year-olds simply replicated the serial ordering of the relations as they occurred in the descriptions. Ondracek and Allen (2000) reached similar conclusions: even though children showed accurate memory for the descriptions, they failed to integrate these descriptions into a coherent mental model or representation of the described space.

Section Summary

The relation between thought and language has re-emerged as topic of great interest in cognitive science. Spatial cognition has proved to be a particularly fruitful domain in which to study this general topic. These studies clearly show the importance of symbols in spatial reasoning. Yet, at the same time, most of the studies do not capture one of the most important characteristics of spatial representation, which is the communication of multiple spatial relations. As we argued in this section, the communication of multiple spatial relations differs fundamentally from the communication of only one or two spatial relations. Thus despite the proliferation of studies on spatial thought and spatial language, we still know very little about the development of the ability to communicate different kinds of spatial information through language. This topic could be a fruitful area for future research.

Maps

Maps are the prototypical way to create a visualization of an environment. They are largely image-driven representations of space. Although maps often use words in labels and keys, most of the information is presented in a very spatial, imagistic way. Such images are not constrained by linearity, allowing them to show many locations and relations simultaneously. They also provide a more stable perspective of the space (often from an overhead view). Both of these factors may make them better candidates than language for conveying route information and complex layouts.

Communicating using images and maps may thus require less inference making and problem solving than the same information represented using words (Larkin & Simon, 1987). Images may also convey the overhead, or *survey*, perspective better than speech. This view can be useful for understanding the layout of a space, as well as the

relations among the locations contained therein (Blaut, 1991; Uttal, 2000). This perspective can be important because we commonly do not have the chance to see the space in this way during navigation. From our perspective on the ground, we usually cannot see all the locations we would like to visit or describe. The distance between locations may be too great and our view may be obscured. To comprehend our environment, we may consolidate our views of different locations and infer where they are in relation to one another. Although people can use the survey perspective when communicating the space with words, they do not often use it consistently (Taylor & Tversky, 1996). The survey perspective is often mixed with the route perspective (i.e., the perspective of someone walking through the space) and the gaze perspective (i.e., the perspective of someone viewing the space from a fixed location). Although these views may provide additional information about the experience of being in the space, they may not convey relational information as effectively as the survey view. Additionally, there may be consequences for memory when learning the space through only the route perspective. With limited exposure (i.e., reading through once), route descriptions lead to perspective-specific memory and require more study time. Even with repeated exposure, reading-time data suggest that route directions are difficult to process. They may be more difficult to integrate into our mental models of a space than the survey view, demanding more complex mental imagery and additional inferences (Brunye, Rapp, & Taylor, 2008; Lee & Tversky, 2005; Noordzij & Postma, 2004).

Developing Understanding of Maps and Models

There has been extensive research on the development of children's understanding of the symbolic relation between maps, photographs, and scale models and the spaces they represent. Indeed, research of this type has proved to be particularly (p. 579) relevant for understanding the development of symbolic thought. In a typical task (e.g., DeLoache, 1987, Loewenstein & Gentner, 2005) a child is asked to find a hidden toy, using the map or model as a guide. The child is shown, for example, where a miniature toy is hiding in the scale model and then is asked to find the corresponding, larger toy in the room that the model represents. Regardless of whether the child succeeds in finding the toy in the room, he or she is brought back to the model and asked to retrieve the miniature toy. Finding the miniature toy proves that any problems in finding the toy in the room could not be due to forgetting where it was located. Therefore, if children fail, it is because they have not understood the relation between the model and the room. Children of 3.0 years succeed in the typical task, but children only 6 months younger typically fail (although some more recent studies have found that 2.5-year-olds can succeed in some situations). However, 2.5-year-olds can succeed when using a photograph instead of the scale model, but 2.0-year-olds cannot.

This line of work has been invaluable in understanding the course of the development of symbolic understanding. However, some researchers (e.g., Blades & Cooke, 1994) have argued that success in the standard DeLoache task does not require that the child map the spatial relations between the model and the room. In the typical DeLoache task, each of the possible hiding locations is unique; there is one chair, one couch, one floor pillow, etc. Therefore, the child never has to discriminate locations on the basis of the spatial location of the objects in the model or the room. For example, the child does not need to remember whether the floor pillow is to the right or left of the couch.

In fact, children less than 4 do have difficulty mapping locations on the basis of spatial relations. For example, Blades and Cooke (1994) included both unique and identical items in a mapping task. When the toy was hidden behind one of the identical objects, the children needed to rely on spatial locations to distinguish between the two. Children less than 4 years could reliably map on the basis of object identity but not on the basis of object identity. For example, if the model included two identical chairs and two other unique objects, the children could not distinguish between the two chairs. Loewenstein and Gentner (2005) showed that mapping on the basis of spatial relations could be enhanced if these relations were embedded within a spatially based language framework. For example, labeling hidden locations as "top, middle, and bottom" substantially improved children's performance. Loewenstein and Gentner suggested that the improvement stemmed from the labels that communicated an organized spatial structure. The children could then use that structure to encode and map the spatial relations between the two models. These results simultaneously confirm the challenges of mapping spatial relations and the possibility of overcoming these challenges. Chen (2007) suggested that noticing the potential analogy between two spaces was part of the challenge for preschoolers, along with initially encoding locations in each space separately, and, once the analogy was noticed, detecting precise correspondences.

There is also work on preschool children's use of maps to guide way finding, which indicates that they show some

ability to use maps in simple situations (e.g., Vosmik & Presson, 2004). In addition, the ability to appreciate scaling relation is present in a rudimentary form in 3-year-old children, but shows development over the next several years (Huttenlocher, Newcombe, & Vasilyeva, 1999; Huttenlocher, Vasilyeva, Newcombe, & Duffy, 2008; Vasilyeva & Huttenlocher, 2004).

Beyond the Preschool Years

The world is not limited to scale models and rooms. Children need to understand maps that represent larger, geographic-scale areas and to develop an appreciation of the various symbols used to convey different kinds of information on maps. Acquiring this sort of information often begins late in the preschool years, but the developmental process last several years. Research on the development of children's understanding and use of maps past the preschool years reveals the importance of studying development beyond the typical young ages that have become the focus of most current developmental research.

Liben and colleagues (e.g., Liben & Downs, 1993; Liben, Kastens, & Stevenson, 2002) have documented a series of developments that occur in children's processing of geographic-scale maps. Interestingly, many of these developments parallel those observed in younger children using smaller-scale maps or scale models. At first, children often seem not to fully grasp that the map is intended to be a representation of a space. For example, when children are asked to identify features on a map, they sometimes name features that violate the scale of the map. For example, when examining a map of Chicago, one child correctly identified Lake Michigan but then claimed to be able to see (p. 580) fishes in lake—a perception that would not be possible at the scale at which the map was drawn.

These findings should not be interpreted in a dichotomous fashion as whether children "can" or "cannot" read maps (see Liben & Downs, 1997). Even 3-year-olds can identify some features on maps, but their identification seems to be limited to situations in which there is a high degree of similarity between the represented item on the map and the intended referent. For example, children often succeed when identifying water on maps, presumably because the water is colored blue, both on the map and in the space the map represents. But children have much more difficulty when asked to identify or understand correspondences that are not based solely on physical similarity. In fact, physical similarity seems to get in the way, or children have a strong belief that there should be a degree of physical similarity between the map and what it represents. For example, one child claimed that a red line on a map could not represent a road (when in fact it did represent a major highway) because there are no red roads on the map. Similarly, another child claimed that a line on a map could not represent a road because it was too small to accommodate a car.

These and other examples clearly show that the development of an understanding both of the representational nature of maps and the spatial correspondences between maps and their referents is not an easy or all-or-none process. Like many other forms of development, it probably develops in fits and starts (e.g., Opfer & Siegler, 2007). Knowledge of the representational components of maps likely can coexist or even compete with interpretations that are based on the physical properties of the referent. Children can demonstrate their nascent knowledge of the representational relation between a map and a geographic-scale space under certain conditions—high similarity, familiarity with the space the map represents, etc. But even in the same testing session, children can be affected by the physical properties of the representation itself. Part of development of map-reading skill, like many other developments, may involve learning to coordinate these alternate construals, to focus on one and suppress the other, etc. Executive control plays an important role in map reading, as it does in many other forms of cognitive development (e.g., Zelazo, 2004).

Cognitive Consequences of Map Use

It seems possible that over time, the use of maps may contribute to spatial thinking. Maps bring into view a perspective on the world that differs fundamentally from the perspective from which we typically navigate. Using this perspective may have cognitive consequences, by making children (and adults) aware of the possibility of thinking about spaces in ways that transcend how they normally navigate through them. Maps may be a cognitive tool or scaffold that help people to overcome and hence to think about the limitations of their own perception.

Although researchers often refer to mental representations as "cognitive maps," as mentioned earlier, the psychological or neural existence of true cognitive maps remains a topic of great debate. Previously, we have

argued that learning about maps might bring into conscious awareness information about relations that have not been experienced directly. For example, although we might have great difficulty inferring relations that we have not experienced directly, we might easily gain this information from looking at a map. The use of maps might bring into awareness the possibility of thinking about spatial relations we have not experienced directly before.

Evidence to support this claim comes from a variety of sources. Some studies, for example, have shown that exposing children to a map can help them both to represent and to communicate spatial relations among locations. Showing 4- to 6-year-olds maps can facilitate inference making and the process of spatial integration (Uttal, Fisher, & Taylor, 2006; Uttal & Wellman, 1989). In addition, learning about maps can help children make inferences about the relations between locations in their neighborhood, even when the children have not experienced these relations directly (Davies & Uttal, 2007).

Gesture

Gesturing involves the movement of hands across space. Like the images in maps, gestures can represent different objects or locations and can indicate direction. These elements make gesture seem like it uses images to communicate information. However, unlike maps, gestures are constrained to representing only two elements simultaneously. This constraint is a consequence of having only two hands (sometimes only one, if we are carrying something or are injured). If we represent more than two locations or objects at a time, this information would be tied to a sequence. Additionally, gesture often requires speech in order to be understood.

Gestures can visually convey information. McNeiil (1992) described speech and gesture as an “idea unit,” with the gestures conveying imagery. Among other things, gestures can represent objects (p. 581) or locations (Cassell & McNeill, 1991; Emmorey, Tversky, & Taylor, 2000), indicate direction (Allen, 2003), indicate relative size or position (Beattie & Shovelton, 1999), and show motion (Ehrlich, Levine, & Goldin-Meadow, 2006; Feyereisen & Havard, 1999). The ability of gesture to convey visual information makes it a good candidate for depicting spatial information during discourse.

Like speech and maps, gestures can convey information about spatial layouts and the experience of moving through space. However, gestures can look a lot like maps. In Figure 20.3, a person describes information about Chicago’s museums as he would describe it to a tourist. The right panel shows a map of the same museum area. To describe the relations among the museums, he uses one hand to represent the Art Institute of Chicago and the other to represent the Field Museum. The placement of his two hands is roughly parallel to the relation between the two symbols on the map.

In Figures 20.4a–c, he describes how a tourist could travel between the two museums by tracing a path and indicating the location of the underpass that would help the tourist avoid crossing Lakeshore Drive. Although this underpass is not indicated on the map in Figure 20.3, this information could be shown in a sketch map (Fig. 20.4d). The sketch map also depicts the route and shows an area indicating the underpass.

Although gestures can capture some of the elements of maps, they have two major differences: gestures are more fleeting than maps and gestures can be tied to a sequence. Gestures are visible but they are temporary; to comprehend multiple gestures, a listener must watch the sequence and combine the individual units. These features are more closely aligned to speech. Words are fleeting because they leave no tangible trace behind (although they can make a lasting impression) and are sequential because of the linear nature of language.

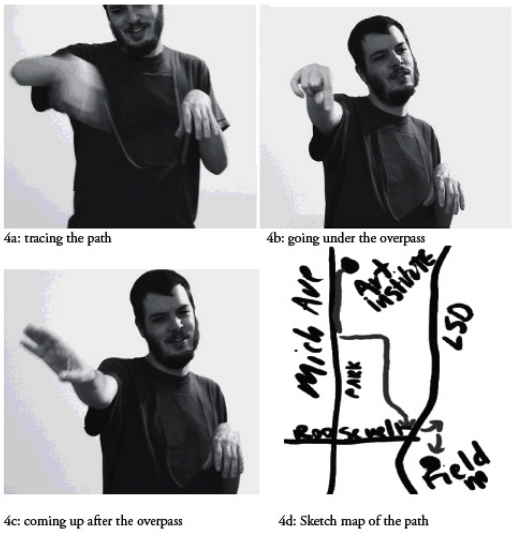
Additionally, gesture often occurs during speech. Gestures often need context for their meaning to be resolved. Goldin-Meadow (2005) gives the example of a gesture that could be interpreted differently under two contexts: consider a rotating gesture made with a pointing hand. The gesture refers to a ballerina’s movements when the speaker says, “She does lovely pirouettes.” However, the same gesture refers to a hand twisting off a jar lid when the speaker says, “Which direction shall I turn this?” (p. 7).

Speech and gesture form a mutually beneficial partnership in which speech can resolve gesture’s meaning and gesture can augment speech. Gestures can resolve the perspective-switching issue by revealing which perspective the speaker is currently using (Kita, Danziger, & Stolz, 2001). In some spatial communication, gesture actually accounts for a sizable proportion of information. Bergman and Kopp (2006) analyzed the distribution of information across speech and gesture for students giving directions. Participants communicated over half of the

spatial information (51.38%) using only their gestures. In other words, an interlocutor who could not see the speaker's hands would be receiving only about half of the information communicated.

Click to view larger

Figure 20.3 . A person describes the relation between the Art Institute (his left hand) and the Field Museum (his right hand) from the point of view of facing the Art Institute (eastward). The right panel shows a map illustrating the relation between the two museums.



Click to view larger

Figure 20.4 . A person describes how a tourist could travel between the two museums by tracing a path and indicating the location of the underpass that would help the tourist avoid crossing Lakeshore Drive.

In summary, gesture lies somewhere in the middle of the image–language continuum. Gesture is able to communicate spatial information in a visual (p. 582) manner, similarly to maps. However, these images are fleeting and often sequential. Although gesture can add to speech, gesture also needs speech in order to be resolved. Gesture is a form of imagery that is intimately tied to speech.

Research on the Development of Gesture Use

Despite the potential importance of gesture in spatial cognition (e.g., Alibali, 2005), it has received far less attention than language or maps have. Most of the studies that have been done have focused on the use of gesture to communicate route information. For example, Allen (2003) and Iverson (1999) showed that young children's spatial gestures often indicate the route that was followed or should be followed, rather than the spatial relations among locations along the route.

More recently, Sauter and colleagues (2012) have investigated the development of children's use of gesture to communicate spatial information, particularly the relative position of locations. The participants (8- and 10-year-olds and adults) first learned the layout of a space by navigating through it several times. They were then asked to communicate the locations of the animals to their mother or father.

Adults tended to use both speech and gesture when describing the locations. They often began by providing an overall description, usually in speech, of the overall layout of the space. The most common way this was done was

by describing the space in matrix language terms, such as by saying, “It was a 3 × 2.” They often augmented their descriptions with gestures. For example, they often placed one hand down and depicted progress through the speech relative to this fixed hand. Then they would provide the identity of the animal at each location. Thus speech and gesture interacted in a reciprocal or redundant way; the spatial descriptions seamlessly combined speech and gesture, and the adults used the affordances of each form of symbolic representation to communicate aspects of the elements of the locations.

In contrast, 8-year-olds provided very little, if any, information about the relation among the locations, either in speech or gesture. Their descriptions tended to focus on the route they had followed when first learning the locations. They seldom gestured. However, a follow-up study showed that the children *could* gesture if encouraged to do so. The (p. 583) instructions were simply, “You can use your hands to show where the animals live.” Eight of the 11 participants responded favorably to these instructions, gesturing frequently. Perhaps more importantly, the appearance of their gestures often resembled those of the adults. Thus, 8-year-olds can use gesture to communicate spatial layout, but they do not do so spontaneously.

Section Summary

Human spatial cognition shares both important similarities and differences with spatial cognition in other species. All species face the basic challenges of representing objects and the relations between objects. Likewise, all mobile species must be able to find their way back to their home, be it a burrow, den, or townhouse. Thus, in one sense, the search for cross-species similarities has been quite successful.

But there is also one very important difference between human and nonhuman species. In humans, symbolic communication greatly enhances what we know about space and how we know it. For example, our language can influence which spatial frames of reference we use habitually. Likewise, maps and gesture can augment substantially the kinds of information we can perceive. Thus, to a large extent, the development of spatial cognition beyond the first few years of life is largely about the influences of symbols on spatial thought and communication.

How to Use What We Know

We have demonstrated in several ways (e.g., meta-analyses, experiments, computational modeling) that spatial skills are highly malleable; therefore, we see spatial skills as a domain in which education could make a large difference. Education aimed at improving spatial skills could affect not only spatial reasoning itself but also the STEM disciplines, such as mathematics, engineering, and the geosciences, in which spatial thinking plays a critically important role.

Despite the importance of education for spatial thinking, it is the orphan of the academic curriculum. It is not the focus of intense early instruction, as are reading, writing, and arithmetic. Nor is it generally considered a highly valued intellectual skill to be tested in high-stakes assessment situations, or given a report-card grade. How, then, can we use what we have learned about the malleability of spatial thinking and the importance of education?

The answer is not likely to be establishing “Space” as the next letter after the three R’s. As we argue in this section, a great deal can be done to enhance spatial thinking in educational settings that does not require a separate course or topic. Moreover, making space a separate subject would only serve to separate it more from math and science (a process often termed “siloing”), when in fact spatially based learning can support or enhance the learning of science and mathematics. Thus we favor taking a more integrative approach, in which spatial skills and spatially based education become a natural part or even a focus of ongoing activities in mathematics and science.

Each intervention will probably need to be tailored to the developmental level of the students targeted, and other instructional choices, such as embedding in a task or story context, will need to be considered. Furthermore, each intervention should likely be evaluated in a small-scale controlled way before widespread curriculum changes are made. There are encouraging signs that this kind of research is increasing, both with young children (e.g., Casey, Andrews, Schindler, Kersh, Samper, & Copley, 2008; Casey, Erkut, Ceder, & Young, 2008; Ehrlich et al., 2006; Gentner, Loewenstein, & Hung, 2007) and with college students (Feng, Spence, & Pratt, 2007; Terlecki, Newcombe, & Little, 2008; Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008).

In the remainder of this section we consider several models for integrating spatially enhanced instruction into formal and informal educational opportunities: direct training, informal learning, spatializing the current curriculum, and integrated science approaches.

Direct Spatial Training

Although we do not believe that direct instruction of spatial thinking is likely to be the most common way of teaching spatial skills, there certainly are situations in which it is appropriate, effective, and efficient. One good example is Sorby and Baartmans' (1996, 2000) work on training spatial skills for incoming engineering students. Introductory engineering students who score worse than the 60th percentile on a standardized test of spatial visualization are encouraged to take the course, which provides extensive instruction and experience in several spatial tasks, including the visualization and mental rotation of three-dimensional figures. This research has yielded very promising results, including not only improvement in spatial reasoning but also better achievement in engineering graphics courses. Although more is needed to provide appropriate (p. 584) comparison or control groups, this work clearly shows the possibility of directly training spatial skills for affecting STEM learning.

Informal Learning

Not all spatial skills need to be taught formally in school. Spatial skills may be particularly well learned through informal learning experiences. One particularly good example is the consequences of playing spatially challenging videogames on spatial attention and reasoning. The evidence is quite strong that playing videogames increases visual-spatial attention, that this effect is causal in nature, and that it transfers to other tasks (Gee, 2007; Green & Bevalier, 2003, 2006; Spence & Feng, 2010; Subrahmanyam & Greenfield, 1996). For example, Green and Bevalier (2003) found that playing *Medal of Honors* was associated with better visual-spatial attention, enumeration, and several other spatial skills. In the same paper, the authors reported the results of an experimental study of non-videogame players showed that learning to play video games confers these advantages, and thus there is a causal relation between videogame playing and spatial thinking.

Informal spatial education need not be limited to videogame playing (Benjamin, Haden, & Wilkerson, 2010). For example, informal building activities in museums can provide an opportunity for parents and children to practice the communication and learning of spatial information. Likewise (http://www.ultimateblockparty.com/), Hirsh-Pasek organized a very large "block party" in New York City that emphasized the importance of play, including spatially focused play, in early development and learning.

Spatializing the Existing Curriculum

There are many ways to affect existing mathematics and science curricula without offering specific training in spatial skills. We use the term *spatializing* to refer to emphasizing the spatial components of skills that are already taught in school. This approach to curriculum can benefit from what we are learning about spatial development and about symbolic communication in the spatial domain, including the use of spatial language, maps and models, and gesture. For example, measurement is a common problem across many areas of math and science. Measurement is, at its core, a spatial concept, one that requires a person to use spatial skills to compare one length to a standard, such a ruler (Newcombe, 2010). Many of the challenges that children face in learning to measure can be both understood and redressed by taking into account the spatial properties of measurement. For example, young children may not realize that all measurements of length must begin at the same point, and that this point corresponds to zero on a ruler (Miller & Baillargeon, 1990; Newcombe, 2010). By considering the role of spatial reasoning in measurement, teachers can more effectively anticipate and address these misconceptions. Many more concepts in science and mathematics also have important connections to spatial thinking. For example, teaching children about the causes of the seasons requires that they imagine transformation of the earth's tilt along its axis at different times of the year. Helping teachers and their students to think about the role of spatial reasoning in learning could have substantial benefits across the mathematics and science curriculum.

Integrative Science Approaches

Spatial thinking can provide a foundation for an integrative approach to teaching science and mathematics. For

example, Kolvoord, Charles, and Purcell (in press) have emphasized spatial thinking in their *Geospatial Semester*, an elective, semester-long course for high-school students. The course focuses on using spatial reasoning and technologies, such as Geographical Information Systems (GIS), to analyze and propose solutions for real-world problems. For example, students have created final projects in which they analyze the optimal placement of wind farms off the coasts of the United States or small hydroelectric production plants in the Philippines. These projects require that students think systematically about many different factors, and spatial visualizations of different data sets become critically important for effective problem solving.

Another example of an integrative approach is the teaching of engineering in K–12 education. Several curricula now exist that emphasize construction of simple structures, such as model windmills or bridges. Engineering emphasizes STEM-relevant problem-solving skills, including defining a problem, considering different solutions, testing hypotheses, and generalizing across examples. Engineering integrates science and mathematics, makes these topics accessible and interesting to young children, and provides focused, tractable projects that teachers can integrate into their classroom activities (Carlson & Sullivan, 2004; Cunningham, 2009; National Research Council, 2009). Although engineering is not an exclusively (p. 585) spatial topic, it often involves spatial thinking and transformation.

Summary

In this chapter, we have suggested that there are two distinct sets of spatial skills: interobject representations and processes relevant to navigation, and intraobject representations and processes relevant to tool making. We know a good deal about the development of interobject cognition, as used for navigation, although research in this area has largely neglected the analysis of individual differences and their development. Representations of the environment change in many ways over the first decade of life. An emerging perspective emphasizes the value of detailed analysis of how children learn which cues to rely on and how to weight these cues optimally. Knowledge about intraobject spatial cognition, used for tool making, has a much richer tradition of assessment of individual differences, as well as some information about developmental sequences. Object representations develop over the first year of life, as infants explore the world visually and manually and gather evidence about it. The ability to imagine transformations of objects also develops, over an age range extending through the toddler and preschool years.

Human spatial cognition shares both important similarities and differences with spatial cognition in other species. But there is also one very important difference between human and nonhuman species, namely the fact that symbolic communication greatly enhances what we know about space and how we know it. For example, our language can influence which spatial frames of reference we use habitually. Likewise, maps and gesture can augment substantially the kinds of information we can perceive. Thus, to a large extent, the development of spatial cognition beyond the first few years of life is largely about the influences of symbols on spatial thought and communication.

Questions for Future Research

1. What is the best formal description of intraobject transformation skills?
2. How can we best explore the sources of individual differences in navigation-relevant skills?
3. Are the two classes of skill completely distinct, no more correlated than any cognitive skills are with each other, or are there some deeper relationships?
4. How are the spatial and numerical systems intertwined and differentiated?
5. How can we best apply data on spatial development to education that fosters spatial literacy?
6. What kinds of early educational practices are most likely to lead to long-term learning?
7. What kinds of formal and informal experiences in spatial reasoning promote STEM learning?
8. What is the best time to start spatial education? What sorts of compensatory experiences or training can be designed to aid students who have relatively little experience early on?

References

Acredolo, L. (1990). Behavioral approaches to spatial orientation in infancy. *Annals of the New York Academy of Sciences*, *608*, 596–612.

Alibali, M. W. (2005). Gesture in spatial cognition: Expressing, communicating, and thinking about spatial information. *Spatial Cognition and Communication*, *5*(4), 307–331.

Allen, G. L. (2003). Gestures accompanying verbal route directions: Do they point to a new avenue for examining spatial representations? *Spatial Cognition and Computation*, *3*(4), 259–268.

Atkinson, J., & Nardini, M. (2008). The neuropsychology of visuospatial and visuomotor development. In J. Reed & J. Warner Rogers (Eds.), *Child neuropsychology: Concepts, theory and practice.* Wiley-Blackwell.

Baber, C. (2003). *Cognition and tool use: Forms of engagement in human and animal use of tools.* London: Taylor & Francis.

Baddeley, A. (1986). *Working memory.* New York: Oxford University Press.

Baenninger, M. A., & Newcombe, N. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles*, *20*, 327–344.

Baillargeon, R., Spelke, E. S., & Wasserman, S. (1985). Object permanence in five-month-old infants. *Cognition*, *20*, 191–208.

Beattie, G., & Shovelton, H. (1999). Mapping the range of information contained in the iconic hand gestures that accompany spontaneous speech. *Journal of Language and Social Psychology*, *18*, 438–462.

Benjamin, N., Haden, C. A., & Wilkerson, E. (2010). Enhancing building, conversation, and learning through caregiver-child (p. 586) interactions in a children's museum. *Developmental Psychology*, *46*(2), 502–515

Bergman, K., & Kopp, S. (2006). Verbal or visual? How information is distributed across speech and gesture in spatial dialog. *Proceedings of the 10th Workshop on the Semantics and Pragmatics of Dialogue* (pp. 90–97).

Blades, M., & Cooke, Z. (1994). Young children's ability to understand a model as a spatial representation. *Journal of Genetic Psychology*, *155*(2), 201–218.

Blaut, J. (1991). Natural mapping. *Transactions of the British Geographers*, *16*, 55–74.

Bullens, J., Nardini, M., Doeller, C. F.,Braddick, O., Postma, A., & Burgess, N. (2010). The role of landmarks and boundaries in the development of spatial memory. *Developmental Science*, *13*, 170–180.

Brunye, T. T., Rapp, D. N., & Taylor, H. A. (2008). Representational flexibility and specificity following spatial descriptions of real-world environments. *Cognition*, *108*, 418–443.

Burmann, B., Dehnhardt, G., & Mauck, B. (2005). Visual information processing in the lion-tailed macaque (*Macaca silenus*): Mental rotation or rotational Invariance? *Brain, Behavior and Evolution*, *65*, 168–176.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies.* New York: Cambridge University Press.

Carlson, L. E., & Sullivan, J. F. (2004). Exploiting design to inspire interest in engineering across the K-16 engineering curriculum. *International Journal of Engineering Education*, *20*(3), 372–378.

Casasola, M., Bhagwat, J., & Burke, A. S. (2009). Learning to form a spatial category of tight-fit relations: How experience with a label can give a boost. *Developmental Psychology*, *45*, 711–723.

Casey, B. M., Andrews, N., Schindler, H., Kersh, J. E., Samper, A., & Copley, J. (2008). The development of spatial skills through interventions involving block building activities. *Cognition and Instruction*, *26*, 269–309.

Casey, B., Erkut, S., Ceder, I., & Young, J. M. (2008). Use of a storytelling context to improve girls' and boys' geometry skills in kindergarten. *Journal of Applied Developmental Psychology*, *29*, 29–48.

Cassell, J., & McNeil, D. (1991). Gesture and the poetics of prose. *Poetics Today*, *12*(3), 375–404.

Chatterjee, A. (2008). The neural organization of spatial thought and language. *Seminars in Speech & Language*, *29*, 226–238.

Chen, Z. (2007). Learning to map: Strategy discovery and strategy change in young children. *Developmental Psychology*, *43*, 386–403.

Cheng, K., Shettleworth, S. J., Huttenlocher, J., & Rieser, J. J. (2007). Bayesian integration of spatial information. *Psychological Bulletin*, *133*, 625–637.

Cheng, K. (2008). Whither geometry? Troubles of the geometric module. *Trends in Cognitive Sciences*, *12*, 355–361.

Cordes, S., & Brannon, E. M. (2009). Crossing the divide: Infants discriminate small from large numerosities. *Developmental Psychology*, *45*, 1583–1594.

Craton, L. G., Elicker, J., Plumert, J. M., & Pick, H. L. (1990). Children's use of frames of reference in spatial communication. *Child Development*, *61*, 1528–1543.

Creem, S. H., Wraga, M., & Proffitt, D. R. (2001). Imagining physically impossible self-rotations: Geometry is more important than gravity. *Cognition*, *81*, 41–64.

Cronbach, L. J. (1957). The two disciplines of scientific psychology. *American Psychologist*, *12*, 671–684.

Cunningham, C. M. (2009). Engineering is elementary. *The Bridge*, *30*(3), 11–17.

Davies, C., & Uttal, D. H. (2007). Map use and the development of spatial cognition. In J. M. Plumert & J. P. Spencer (Eds.), *The emerging spatial mind* (pp. 219–247). New York: Oxford University Press.

DeLoache, J. S. (1987). Rapid change in the symbolic functioning of very young children. *Science*, *238*, 1556–1557.

Doeller, C. F., King, J. A., & Burgess, N. (2008). Parallel striatal and hippocampal systems for landmarks and boundaries in spatial memory. *Proceedings of the National Academy of Sciences USA*, *105*, 5915–5920.

Ehrlich, S., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology*, *42*, 1259–1268.

Emmorey, K., Tversky, B., & Taylor, H. A. (2000). Using space to describe space: Perspective in speech, sign, and gesture. *Spatial Cognition and Computation*, *2*(3), 157–180.

Epstein, R. A. (2008). Parahippocampal and retrosplenial contributions to human spatial navigation. *Trends in Cognitive Sciences*, *12*, 388–396.

Estes, D. (1998). Young children's awareness of their mental activity: The case of mental rotation. *Child Development*, *69*, 1345–1360.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*, 307–314.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science*, *18*, 850–855.

Feyereisen, P., & Havard, I. (1999). Mental imagery and production of hand gestures while speaking in younger and older adults. *Nonverbal Behavior*, *23*, 153–171.

Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental Science*, *8*, 402–408.

Frick, A., Daum, M. M., Walser, S., & Mast, F. W. (2009). Motor processes in children's mental rotation. *Journal of Cognition and Development*, *10*, 18–40.

Frick, A., Daum, M. M., Wilson, M., & Wilkening, F. (2009). Effects of action on children's and adults' mental imagery. *Journal of Experimental Child Psychology*, *104*, 34–51.

Frick, A., Wang, S. (2009, April). *Round and round it goes: Mental rotation in 14- and 16-month-olds.* Society for Research in Child Development, Denver, CO, USA.

Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: Bradford Books/MIT Press.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences*. New York: Basic Books.

Gentner, D., Loewenstein, J., & Hung, B. (2007). Comparison facilitates children's learning of names for parts. *Journal of Cognition and Development*, *8*, 285–307.

Goldin-Meadow, S. (2005). *Hearing gesture: How our hands help us think.* Cambridge, MA: Harvard University Press.

Gee, J. P. (2007). *What video games have to teach us about learning and literacy*. New York: Palgrave.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*(6939), 534–537. **(p. 587)**

Green, C. S., & Bavelier, D. (2006). Enumeration versus multiple object tracking: The case of action video game players. *Cognition*, *101*(1), 217–245.

Haun, D. B. M., Rapold, C. J., Call, J., Janzen, G., & Levinson, S. C. (2006). Cognitive cladistics and cultural override in Hominid spatial cognition. *Proceedings of the National Academy of Sciences USA*, *103*(46), 17568–17573.

Haith, M. M. (1998). Who put the cog in infant cognition? Is rich interpretation too costly? *Infant Behavior & Development*, *21*, 167–179.

Hegarty, M., Keehner, M., Khooshabeh, P., & Montello, D. R. (2009). How spatial abilities enhance, and are enhanced by, dental education. *Learning and Individual Differences*, *19*, 61–70.

Hegarty, M., Montello, D. R., Richardson, A. E., Lovelace, K., & Ishikawa, T. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence*, *34*, 151–176.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence*, *32*, 175–191.

Hegarty, M., & Waller, D. A. (2005). Individual differences in spatial abilities. In P. Shah & A. Miyake (Eds.), *The Cambridge handbook of visuospatial thinking* (pp. 121–169). New York: Cambridge University Press.

Hermer, L., & Spelke, E. S. (1994). A geometric process for spatial reorientation in young children. *Nature*, *370*, 57–59.

Hespos, S. J., & Rochat, P. (1997). Dynamic mental representation in infancy. *Cognition*, *64*, 153–188.

Holden, M. P., & Newcombe, N. S. (in press). The development of adaptive spatial processing. In Nadel, L., & Waller, D. (Eds.), *Handbook of spatial cognition*. Washington, DC: APA Books.

Hund, A. M., & Naroleski, A. R. (2008) Developmental changes in young children's spatial memory and language in relation to landmarks. *Journal of Cognition and Development*, *9*, 310–339.

Hund, A. M., & Plumert, J. M. (2007). What counts as by? Young children's use of relative distance to judge nearbyness. *Developmental Psychology*, *43*, 121–133.

Huttenlocher, J., &Lourenco, S. F. (2007). Using spatial categories to reason about location. In J. M. Plumert & J. P. Spencer (Eds.), *The emerging spatial mind* (pp. 3–24). New York: Oxford University Press.

Huttenlocher, J., Newcombe, N., & Vasilyeva, M. (1999). Spatial scaling in young children. *Psychological Science*, *10*, 393–398.

Huttenlocher, J., & Presson, C. C. (1973). Mental rotation and the perspective problem. *Cognitive Psychology*, *4*, 277–299.

Huttenlocher, J., & Presson, C. C. (1979). The coding and transformation of spatial information. *Cognitive Psychology*, *11*, 375–394.

Huttenlocher, J., Vasilyeva, M., Newcombe, N., & Duffy, S. (2008). Developing symbolic capacity one step at a time. *Cognition*, *106*, 1–12.

Iverson, J. M. (1999). How to get to the cafeteria: gesture and speech in blind and sighted children's spatial descriptions. *Developmental Psychology*, *35*(4), 1132–1142.

Jacobs, L. F., & Schenk, F. (2003). Unpacking the cognitive map: The parallel map theory of hippocampal function. *Psychological Review*, *110*, 285–315.

Johnson, S. P. (2009a). Developmental origins of object perception. In A. Woodward & A. Needham (Eds.), *Learning and the infant mind* (pp. 47–65). New York: Oxford University Press.

Johnson, S. P. (Ed.) (2009b). *Neoconstructivism: The new science of cognitive development.* New York: Oxford University Press.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Payne, T. W., Engle, R. W., & Wilhelm, O. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*, 189–217.

Kastens, K. A., Manduca, C. A., Cervato, C., Frodeman, R., Goodwin, C., Liben, L. S., Mogk, D. W. Spangler, T. C. Stillings, N. A., & Titus, S. (2009). How geoscientists think and learn. *Eos, Transactions of the American Geophysical Union*, *90*, 265–266.

Keen, R. (2003). Representation of objects and events: Why do infants look so smart and toddlers look so dumb? *Current Directions in Psychological Science*, *12*, 79–83.

Kellman, P. J., & Spelke, E. S. (1983). Perception of partly occluded objects in infancy. *Cognitive Psychology*, *15*, 483–524.

Kelly, J. W., McNamara, T. P., Bodenheimer, B., Rieser, J. J., & Carr, T. H. (2008). The shape of human navigation: How environmental geometry is used in maintenance of spatial orientation. *Cognition*, *109*, 281–286.

Kenward, B., Weir, A. A. S., Rutz, C., & Kacelnik, A. (2005). Tool manufacture by naive juvenile crows. *Nature*, *433*, 121.

Kita, S., Danziger, E., & Stolz, C. (2001). Cultural specificity of spatial schemas as manifested in spontaneous gestures. In M. Gattis (Ed.), *Spatial schemas in abstract thought* (pp. 115–146). Cambridge, MA: MIT Press.

Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009). Recruitment of an area involved in eye movements during mental arithmetic. *Science*, *324*, 1583–1585.

KöKöhler, C.,Hoffmann, K. P.,Dehnhardt, G., & Mauck, B. (2005). Mental rotation and rotational invariance in the rhesus monkey (*Macaca mulatta*). *Brain, Behavior and Evolution*, *66*, 158–166.

Kolvoord, R. A., Charles, M., & Purcell, S. (in press). What happens after the professional development: Case studies on implementing GIS in the classroom. In J. MaKinster, N. Tratman, & M. Barnett (Eds.), *Teaching science and investigating environmental issues with geospatial technology*. New York: Springer Publishing.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition*, *29*, 745–756.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science*, *31*, 549–579.

Krøjgaard, P. (2007). Comparing infants' use of featural and spatiotemporal information in an object individuation task using a new event-monitoring design. *Developmental Science*, *10*, 892–909.

Landau, B., Spelke, E. S., & Gleitman, H. (1984). Spatial knowledge in a young blind child. *Cognition*, *16*, 225–260.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, *11*, 65–100.

Learmonth, A. E., & Newcombe, N. S. (2010). The development of place learning in comparative perspective. In F. Dolins & R. Mitchell (Eds.), *Spatial cognition: Mapping the self and space* (pp. 520–538). Cambridge University Press.

(p. 588) Lee, P. U., & Tversky, B. (2005). Interplay between visual and spatial: The effect of landmark descriptions on comprehension of route/survey spatial descriptions. *Spatial Cognition and Computation*, *5*, 163–185.

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*, 940–949.

Levinson, S. (1996). Frames of reference and Molyneux's question: Crosslinguistic evidence. In P. Bloom & M. Peterson (Eds.), *Language and space* (pp. 109–169). Cambridge, MA: MIT Press.

Levinson, S. C. (2003). *Space in language and cognition: Explorations in cognitive diversity*. Cambridge: Cambridge University Press.

Li, P., & Gleitman, L. (2002). Turning the tables: language and spatial reasoning. *Cognition*, *83* (3), 265–294.

Li, P., & Shusterman, A. (2007). *Children's acquisition of spatial frame-of-reference terms*. Paper presented at the Boston University Conference on Language Development. Boston, MA.

Liben, L. S. (2006). Education for spatial thinking. In K. A. Renninger & I. E. Sigel (Volume Eds.), W. Damon & R. M. Lerner (Chief Eds.), *Handbook of child psychology, 6th ed.: Vol. 4, Child psychology in practice* (pp. 197–247). Hoboken, NJ: John Wiley & Sons Inc.

Liben, L. S., & Downs, R. M. (1993). Understanding person-space-map relations: Cartographic and developmental perspectives. *Developmental Psychology*, *29*(4), 739–752

Liben, L. S., & Downs, R. M. (1997). Can-ism and Can'tianism: A straw child. *Annals of the Association of American Geographers*, *87*(1), 159–167.

Liben, L. S., Kastens, K. A., & Stevenson, L. M. (2002). Real-world knowledge through real-world maps: A developmental guide for navigating the educational terrain. *Developmental Review*, *22*(2), 267–322.

Loewenstein, J., & Gentner, D. (2005). Relational language and the development of relational mapping. *Cognitive Psychology*, *5*(4), 315–353.

Lourenco, S. F., & Longo, M. R. (2010). General magnitude representation in human infants. *Psychological Science*, *21*, 873–881.

Marmor, G. S. (1975). Development of kinetic images: When does the child first represent movement in mental images? *Cognitive Psychology*, *7*, 548–559.

Marmor, G. S. (1977). Mental rotation and number conservation: Are they related? *Developmental Psychology*, *13*, 320–325.

McGrew, K. S. (2009). CHC theory and the human cognitive abilities project: Standing on the shoulders of the giants of psychometric intelligence research. *Intelligence*, *37*, 1–10.

McNeill, D. (1992). *Hand and mind. What gestures reveal about thought.* Chicago: University of Chicago Press.

Miller, G. A. (1969). Psychology as a means of promoting human welfare. *American Psychologist*, *24*, 1063–1075.

Miller, K. F., & Baillargeon, R. (1990). Length and distance: Do preschoolers think that occlusion brings things together? *Developmental Psychology*, *26*(1), 103–114.

Mix, K. S., Huttenlocher, J., & Levine, S. C. (2002). *Quantitative development in infancy and early childhood.* New York: Oxford University Press.

Moore, D. S., & Johnson, S. P. (2008). Mental rotation in human infants: A sex difference. *Psychological Science*, *19*, 1063–1066.

Munakata, Y., McClelland, J. L., Johnson, M. H., & Siegler, R. S. (1997). Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review*, *104*, 686–713.

Nadel, L., & Waller, D. (in press). *Handbook of spatial cognition.* Washington, DC: APA Books.

Nardi, D., & Bingman, V. P. (2009). Pigeon (*Columba livia*) encoding of a goal location: The relative importance of shape geometry and slope information. *Journal of Comparative Psychology*, *123*, 204–216.

Nardini, M., Burgess, N., Breckenridge, K., & Atkinson, J. (2006). Differential developmental trajectories for egocentric, environmental and intrinsic frames of reference in spatial memory. *Cognition*, *101*, 153–172.

Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology*, *18*, 689–693.

Nardini, M., Thomas, R. L., Knowland, V. C. P., Braddick, O. J., & Atkinson, J. (2009). A viewpoint-independent process for spatial reorientation. *Cognition*, *112*, 241–248.

National Research Council (2006). *Learning to think spatially.* Washington, DC.: National Academies Press.

National Research Council (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. Washington, DC: National Academies Press.

Needham, A., & Baillargeon, R. (2000). Infants' use of featural and experiential information in segregating and individuating objects: A reply to Xu, Carey and Welch (2000). *Cognition*, *74*, 255–284.

Needham, A. (2009). Learning in infants' object perception, object-directed action, and tool use. In A. Woodward & A. Needham (Eds.), *Learning and the infant mind* (pp. 208–226). New York: Oxford University Press.

Newcombe, N. (1989). The development of spatial perspective taking. In H. W. Reese (Ed.), *Advances in child development and behavior* (Vol. 22, pp. 203–247). New York: Academic Press.

Newcombe, N. S. (2002a). Spatial cognition. In D. Medin (Ed.), *Cognition Volume, Stevens' Handbook of Experimental Psychology* (3rd ed., pp. 113–163). New York: Wiley.

Newcombe, N. S. (2002b). The nativist-empiricist controversy in the context of recent research on spatial and quantitative development. *Psychological Science*, *13*, 395–401.

Newcombe, N. S. (2010a). What is neoconstructivism? In S. P. Johnson (Ed.), *Neoconstructivism: The new science of cognitive development* (pp. v–viii). New York: Oxford University Press.

Newcombe, N. S. (2010b). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator*, *8*, 29–43.

Newcombe, N., & Huttenlocher, J. (1992). Children's early ability to solve perspective-taking problems. *Developmental Psychology*, *28*, 635–643.

Newcombe, N. S., & Huttenlocher, J. (2000). *Making space: The development of spatial representation and reasoning*. Cambridge, MA: MIT Press.

Newcombe, N. S., & Huttenlocher, J. (2006). Development of spatial cognition. In D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology* (6th ed., pp. 734–776). John Wiley.

Newcombe, N., Huttenlocher, J., & Learmonth, A. (1999). Infants' coding of location in continuous space. *Infant Behavior & Development*, *22*, 483–510.

(p. 589) Noordzij, M. L., & Postma, A. (2004). Categorical and metric distance information in mental representations derived from route and survey descriptions. *Psychological Research*, *69*, 221–232.

Ondracek, P. J., & Allen, G. L. (2000). Children's acquisition of spatial knowledge from verbal descriptions. *Spatial Cognition and Computation*, *2*, 1–30.

Okamoto-Barth, S., & Call, J. (2008). Tracking and inferring spatial rotation by children and great apes. *Developmental Psychology*, *44*, 1396–1408.

Opfer, J. E., & Siegler, R. S. (2007). Representational change and children's numerical estimation. *Cognitive Psychology, 55(3)*, 169–195.

Piaget, J., & Inhelder, B. (1966/1971). *Mental imagery in the child*. Routledge and Kegan Paul.

Plumert, J. M., Ewert, K., & Spear, S. S. (1995). The early development of children's communication about nested spatial relations. *Child Development*, *66*(4), 959–969.

Plumert, J. M., Hund, A. H., & Recker, K. M. (2007). Organism-environment interaction in spatial development: Explaining categorical bias in memory for location. In J. M. Plumert & J. P. Spencer (Eds.), *The emerging spatial mind* (pp. 25–52). New York: Oxford University Press.

Plumert, J. M., Pick, H. L., Marks, R. A., & Kintsch, A. S. (1994). Locating objects and communicating about locations: Organizational differences in children are searching and direction-giving. *Developmental Psychology*, *30*(3), 443–453.

Plumert, J. M., & Spencer, J. P. (Eds.) (2007). *The emerging spatial mind.* New York: Oxford University Press.

Quinn, P. C., & Liben, L. S. (2008). A sex difference in mental rotation in young infants. *Psychological Science*, *19*, 1067–1070.

Rieser, J. J., & Pick Jr., H. L. (2007). Using locomotion to update spatial orientation: What changes with learning and development? In J. M. Plumert & J. P. Spencer (Eds.), *The emerging spatial mind* (pp. 77–103). New York: Oxford University Press.

Rochat, P., & Hespos, S. J. (1996). Tracking and anticipation of invisible spatial transformation by 4- to 8-month-old infants. *Cognitive Development*, *11*, 3–17.

Sandberg, E. H., Huttenlocher, J., & Newcombe, N. (1996). The development of hierarchical representation of two-dimensional space. *Child Development*, *67*, 721–739.

Sauter, M., Uttal, D. H., Alman, A., Goldin-Meadow, S., & Levine, S. (2012). Learning what children know about space from looking at their hands: The added value of gesture to the development of spatial communication, *111*(4), 587–606.

Shea, D. L., Lubinski, D., & Benbow, C. P. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. *Journal of Educational Psychology*, *93*, 604–614.

Shettleworth, S. J. (2009). *Cognition, evolution, and behavior* (2nd ed.). New York: Oxford University Press.

Sholl, M. J. (1988). The relationship between sense of direction and mental geographic updating. *Intelligence*, *12*, 299–314.

Simons, D. J., & Wang, R. F. (1998). Perceiving real-world viewpoint changes. *Psychological Science*, *9*, 315–320.

Smith, L. B. (2009). From fragments to geometric shape: Changes in visual object recognition between 18 and 24 months. *Current Directions in Psychological Science*, *18*(5), 290–294.

Sorby, S. (2009). Educational research in developing 3-D spatial skills for engineering students. *International*

Journal of Science Education, *31*, 459–480.

Sorby, S. A., & Baartmans, B. J. (1996). A course for the development of 3-D spatial visualization skills. *Engineering Design Graphics Journal*, *60*(1), 13–20.

Sorby, S. A., & Baartmans, B. J. (2000). The development and assessment of a course for enhancing the 3-D spatial visualization skills of first year engineering students. *Journal of Engineering Education*, *89*(3), 301–308.

Souman, J. L., Frissen, I., Sreenivasa, M. N., & Ernst, M. O. (2009). Walking straight into circles. *Current Biology*, *19*(18), 1538–1542.

Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental Science*, *10*, 89–96.

Spence, I., & Feng, J. (2010). Video games and spatial cognition. *Review of General Psychology*, *14*(2), 92–104.

Spencer, J. P., & Hund, A. M. (2002). Prototypes and particulars: Geometric and experience-dependent spatial categories. *Journal of Experimental Psychology: General*, *131*, 16–37.

Spencer, J. P., Smith, L. B., & Thelen, E. (2001). Tests of a dynamic systems account of the A-not-B error: The influence of prior experience on the spatial memory abilities of two-year-olds. *Child Development*, *72*, 1327–1346.

Subrahmanyam, K., & Greenfield, P. M. (1994). Effect of video game practice on spatial skills in girls and boys. *Journal of Applied Developmental Psychology*, *15*(1), 13–32.

Taylor, H. A., & Tversky, B. (1996). Perspective in spatial descriptions. *Journal of Memory and Cognition*, *35*, 371–391.

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology*, *22*, 996–1013.

Thinus-Blanc, C., & Gaunet, F. (1997). Representation of space in blind persons: Vision as a spatial sense? *Psychological Bulletin*, *121*, 20–42.

Twyman, A. D., & Newcombe, N. S. (2010). Five reasons to doubt the existence of a geometric module. *Cognitive Science*, *34*, 1315–1356.

Uttal, D. (2000). Seeing the big picture: map use and the development of spatial cognition. *Developmental Science*, *3*(3), 247–286.

Uttal, D. H., Fisher, J. A., & Taylor, H. A. (2006). Words and maps: Developmental changes in mental models acquired from descriptions and depictions. *Developmental Science*, *9*(2), 221–235.

Uttal, D. H., Meadow, N. G., Hand, L. L., Lewis, A. R., Tipton, E., Warren, C., & Newcombe, N. S. (2012). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*. doi: 10.1037/a0028446.

Uttal, D. H., & Wellman, H. M. (1989). Children's mental reresentation of spatial information acquired from maps. *Developmental Psychology*, *25*, 128–138.

Vasilyeva, M., & Huttenlocher, J. (2004). Early development of scaling ability. *Developmental Psychology*, *40*, 682–690.

Vasilyeva, M., & Lourenco, S. F. (2010). Spatial development. In R. Lerner & W. Overton (Eds.), *Handbook of lifespan human development, Vol. 1: Methods, biology, neuroscience and cognitive development* (pp. 720–753). Hoboken, NJ: Wiley.

Vosmik, J. R., & Presson, C. C. (2004). Children's response to natural map misalignment during wayfinding. *Journal of Cognition and Development*, *5*, 317–336. (p. 590)

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*(4), 817–835.

Waisman, A. S., & Jacobs, L. F. (2008). Flexibility of cue use in the fox squirrel (*Sciuris niger*). *Animal Cognition*, *11*, 625–636.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space and quantity. *Trends in Cognitive Sciences*, *7*, 483–488.

Wanzel, K. R., Hamstra, S. J., Anastakis, D. J., Matsumoto, E. D., & Cusimano, M. D. (2002). Effect of visual-spatial ability on learning of spatially-complex surgical skills. *Lancet*, *359*, 230–231.

Waterhouse, L. (2006). Multiple intelligences, the Mozart Effect, and emotional intelligence: A critical review. *Educational Psychologist*, *41*, 207–225.

Webb, R. M., Lubinski, D., & Benbow, C. P. (2007). Spatial ability: A neglected dimension in talent searches for intellectually precocious youth. *Journal of Educational Psychology*, *99*, 397–420.

Wilcox, T., & Baillargeon, R. (1998). Object individuation in infancy: The use of featural information in reasoning about occlusion events. *Cognitive Psychology*, *37*, 97–155.

Wilcox, T., & Woods, R. (2009). Experience primes infants to individuate objects: Illuminating learning mechanisms. In A. Woodward & A. Needham (Eds.), *Learning and the infant mind* (pp. 117–143). New York: Oxford University Press.

Woodward, A., & Needham, A. (Eds.). (2009). *Learning and the infant mind*. New York: Oxford University Press.

Wraga, M., Creem, S. H., & Proffitt, D. R. (2000). Updating displays after imagined object and viewer rotations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*, 151–168.

Wraga, M., Creem-Regehr, S. H., & Proffitt, D. R. (2004). Spatial updating of virtual displays during self and display rotation. *Memory & Cognition*, *32*, 399–415.

Wraga, M., Shephard, J. M., Church, J. A., Kosslyn, S. M., & Inati, S. (2005). Imagined rotations of self versus objects: An fMRI study. *Neuropsychologia*, *43*, 1351–1361.

Wraga, M., Thompson, W. L., Alpert, N. M., & Kosslyn, S. M. (2003). Implicit transfer of motor strategies in mental rotation. *Brain and Cognition*, *52*, 135–143.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review*, *15*, 763–771.

Xu, F. (2008). Rational statistical inference and cognitive development. In P. Carruthers, S. Laurence, & S. Stich (Eds.), *The innate mind, Volume 3: Foundations and the future* (pp. 199–215). New York: Oxford University Press.

Xu, F., & Baker, A. (2005). Object individuation in 10-month-old infants using a simplified manual search method. *Journal of Cognition and Development*, *6*, 307–323.

Xu, F., & Carey, S. (1996). Infants' metaphysics: The case of numerical identity. *Cognitive Psychology*, *30*, 111–153.

Xu, F., Carey, S., & Quint, N. (2004). The emergence of kind-based object individuation in infancy. *Cognitive Psychology*, *49*, 155–190.

Xu, F., & Tenenbaum, J. B. (2007). Word learning as Bayesian inference. *Psychological Review*, *114*, 245–272.

Zelazo, P. D. (2004). The development of conscious control in childhood. *Trends in Cognitive Science*, *8*(1), 12–17.

Notes:

(1) . Note, however, that a large-scale randomized study would be necessary to give this optimism absolutely firm

empirical support.

(2) . However, there are also important differences in conceptualization. In particular, the core-knowledge point of view proposes substantially more restricted definitions than those we presented above.

(3) . Arguably, these two kinds of coding represent egocentrism of different kinds, although Piaget did not distinguish the two meanings. In terms of a modern typology of spatial representation, Piaget believed that infants are dependent on response learning and/or local views or visual snapshots of their environment.

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