Chapter 1

Introduction

This book concerns the development of spatial representation and reasoning. Because spatial cognition is an adaptively vital skill, knowledge of how such skills develop is central to the theoretical goal of understanding human cognitive functioning and to the practical goal of optimizing development of human abilities. Historically, scholars have hoped that cognitive development could be understood in the aggregate, in terms of certain general principles. More recently though it has become clear that separate domains of development require separate analysis. While pursuing such a strategy defers consideration of how integrated functioning arises from the various cognitive tasks humans perform, and of whether there are overarching principles for development, the hope is that more certain understanding of development in particular important domains will ultimately improve the chances of a successful general analysis. At the end of this book, we will consider to what extent current understanding of spatial development in fact informs developmental theory.

In this introductory chapter we begin by discussing at a bit greater length two preliminary matters to which we have already alluded: the importance of the spatial domain, and the strategy of domain-specific analysis as a means for understanding cognitive development. We then survey the three approaches to spatial development that have dominated most prior thinking on the topic: Piagetianism, nativism, and, to a somewhat lesser extent, Vygotskyanism. Finally, we outline the plan for this book.

Why Space?

Spatial competence is a central aspect of human adaptation. Spatial knowledge is essential to life in the world, since anything concretely existing in the world must have some spatial location—perhaps not a known one, but at least a potentially knowable one. The philosophically fundamental aspect of spatial knowledge was most famously discussed by Kant. In addition spatial knowledge is fundamental from a biological point of view. In order to survive and reproduce, all mobile beings must be able to organize their action in the spatial world. Human beings presumably evolved as hunters and foragers in an ecology in which their reproductive fitness was linked to their ability to track wild animals and return home, to find edible vegetation and rejoin a larger group, and to avoid dangers from predators and from the physical environment.

As tool use and artifact making became part of the human repertoire, reproductive advantage likely accrued from being able to imagine and construct useful implements and materials. In the current world, spatial competence is basic to daily activities such as assembling breakfast, walking to work, or fitting large objects into the trunk of a car, and also to higher-level activities such as sophisticated mathematical thinking, using information presented in graphs, diagrams, maps, and other spatial layouts (e.g., diagnostic imaging), and understanding verbal descriptions of spatial material (e.g., as when following instructions on hooking up electronic equipment).

Thus, to understand human cognitive functioning, we must understand how people code the locations of things and navigate around the world, and how they represent and mentally manipulate spatial information. To be successful, spatial coding systems and spatial representations must be based on physical principles that structure the material world. Without at least tolerably close correspondence between internal representations and the actual physical world, we would not be able to find what we need, avoid what we fear, or imagine and construct real tools.

Domain-Specific Analysis

Spatial competence is not only an important aspect of human intelligence, it is also a distinct aspect, separable from other cognitive activities at the behavioral, computational and neurological levels of analysis. At the behavioral level, both psychometric and experimental evidence have led to the identification of distinct spatial representations and thought processes. A spatial factor is one of the most consistent factors to emerge from factor analytic studies of intelligence (e.g., see Carroll 1993), and spatial reasoning seems to involve analogue processes distinct from those involved in verbal reasoning (e.g., see Shepard and Cooper 1982). At the computational level, recent work indicates that while qualitative representations alone are sufficient for certain problems, metric representations are required for successful spatial reasoning by machine (Forbus, Nielsen, and Faltings 1991). At the neurological level, spatial functioning is known to involve distinct brain areas (i.e., the hippocampus, parietal cortex, and areas of prefrontal cortex), as shown by studies involving imaging techniques, single-cell recording, and effects of brain damage. For instance, selective damage to the posterior superior parietal lobes can result in specific spatial deficit, as when a patient can "see" objects clearly (i.e., recognize them, name them, and reach for them when they are visually present) but cannot locate them (i.e., cannot reach for objects with eyes closed or after the objects have been absent for more than a few hundred milliseconds; Stark, Coslett, and Saffran 1996).[1]

Progress in understanding cognitive development requires domain-specific analysis of distinct aspects of intelligence, such as space and language, for several reasons. First, we know that certain capabilities in the adult—including spatial location, as well as language and face recognition to give other examples—are supported by distinct neurological substrates. Charting the developmental course of such neural organization is one of the goals of developmental analysis, and this goal entails domain specificity. In addition knowledge of the mature neural organization usually provides important clues and constraints for theorizing at the behavioral level, and vice versa. Second, characterization of mature competence is a prerequisite to analyzing starting points and developmental change, and such characterization must inevitably be done in domain-specific terms. It makes no sense to speak of mental rotation when thinking about language development nor to speak of the grammatical category of subject when thinking about spatial development. Third, the nature of the information that leads to developmental change differs across domains. Much has been made, for instance, in the study of language development of the lack of feedback to children regarding their syntactic errors (e.g., Pinker 1984, 1994). But this is surely not true of spatial development. Children either find a lost object they are searching for or they don't; they either get lost or they don't.

When we speak of domain-specific analysis, we invite several questions. One of these is: What exactly is a domain? There are many different definitions, associated with very different theoretical perspectives, ranging from Fodor's (1983) modularity to expertise-based areas of developed knowledge, such as ability to play chess (Wellman and Gelman 1992). Implicit in what we have written so far is a view of how to identify domains likely to be productive for developmental analysis. What we mean by a domain is a set of behaviors that meet certain

1. In everyday life, the patient had difficulty finding her way around familiar environments, including even her own house.

criteria: they are important for survival and reproduction, philosophically fundamental, behaviorally and computationally independent of other abilities, and dependent on neurologically specialized mechanisms in the mature brain. These criteria often converge, for good reason. Ontologically fundamental understandings are good candidates for functions that the cognitive system has evolved to perform so as to ensure survival and reproduction. Such functions may be performed by special-purpose neural circuitry in mature organisms, and may follow individual ontogenetic laws.

Note that a commitment to domain-specific analysis does not, in our view, entail a commitment to the idea that there exist innately available autonomously running sets of procedures for dealing with specific adaptive problems (cf. Fodor 1983). Dedicated neural systems in adults, as well as universally observed developmental sequences, may emerge from interaction of biologically based starting points with the environments that infants inevitably or almost inevitably encounter after birth. Such a view is quite different from hypothesizing direct specification at birth of particular representations or procedures (Elman et al. 1996; Thelen and Smith 1994). Development can lead to emergent modularity, but it can go the other way as well. Karmiloff-Smith (1992) proposed that there sometimes exists an early modularity that is punctured in the course of development, such as when perceptual codings become accessible to symbolic representation and verbal description during childhood.

There are dangers as well as virtues to a domain-specific approach to cognitive development. Most notably, investigators of a single domain risk focusing in increasing detail on that domain in isolation from all other aspects of cognitive development. To be successful, a domain-specific approach must involve cognizance of other lines of development. The aim is not only to understand a domain, such as spatial development, but also to relate discoveries about development in the domain to analyses of other domains and of cognitive development more generally. Thus a domain-specific approach to cognitive development is complementary to domain-general discussions of cognitive development, which help remind us of the importance of looking for deep connections (or contrasts) among domains (e.g., Gopnik and Meltzoff 1997; Rogoff 1990; Siegler 1996).

Three Prior Approaches to Spatial Development

There are many theories pertaining to specific aspects of spatial development, such as understanding maps. In this book we will touch on most of these. For now, we want to consider only the three theories of spatial development that have exerted dominant general influences:

Piaget's thinking on space, nativism, and Vygotsky's views on cultural transmission of spatial skills. Each of these approaches has merit, but each has been found to offer only a partial view of spatial development.

Piaget's Approach to Spatial Development

As with many other domains of cognitive development, the initial account of the origins of adult spatial competence is found in Piaget. Piaget (1951, 1952, 1954) argued that infants are born without knowledge of space, and without a conception of permanent objects which occupy and structure that space. He suggested that infants begin by treating objects as defined by their own activity. In this view an object acquires an existence and a location defined by the physical action needed to obtain or manipulate the object or by the perceptual activities needed to see or hear it. From this starting point, Piaget charted the growth of more mature concepts. For instance, he claimed that initial understanding of extent involves qualitative division of the sensory world into the categories of "reachable" (or near) and "unreachable" (or far). This initial notion was said to be centered on the self; decentering (i.e., generalization of the concept of extent to encompass relations not involving the self) was seen as a gradual process, sometimes termed the egocentric-to-allocentric shift.

Writing about spatial development after infancy, Piaget and Inhelder (1948/1967) described qualitatively different stages of thought. They argued that children begin by thinking about spatial location topologically, that is, in terms of continuities and discontinuities—children see objects simply as touching one another, as enclosed one by another, or as separated from each other. More mature spatial coding was said to appear at the age of nine or ten years, in systems called *projective* and *Euclidean space*. Piaget and Inhelder defined projective space as the coding of the order of objects along different lines of projection extended from one referent object to another, and Euclidean space as the coding of objects metrically, with reference to vertical and horizontal reference lines. While projective space seems simpler than Euclidean space in that it involves ordinal rather than metric measurement, projective and Euclidean space were not clearly developmentally sequenced in Piaget's writing (see Newcombe 1989 for further discussion).

Piaget's account of spatial development has inspired a tremendous amount of productive empirical work, literally hundreds of studies of the egocentric-to-allocentric shift, infants' search for objects, preschoolers' responses to distance problems, and elementary school children's ability to copy models or imagine another person's view of a spatial array. In general, much of this research has been critical of Piaget's account of spatial development. Studies have shown that infants begin with more equipment for spatial analysis than Piaget imagined, that preschoolers can reason about distance, and that elementary school children (and even preschoolers) can reason about spatial perspectives.

Each of these research issues is thoroughly treated in this book. In very rough preview, we conclude that Piaget indeed erred in suggesting that many spatial achievements are reached quite late in childhood. We argue that findings of younger children succeeding at versions of his tasks are not always the product of simplifying the tasks to the point where they assess abilities quite different from those of interest to Piaget (as urged in Piaget's defense by Chapman 1988). Such successes tell us something about the growing points in development, just as the failures tell us what remains to be accomplished. In addition, perhaps inadvertently, Piaget erred in implying that adults are accurate in spatial tasks; important errors and biases exist in mature spatial coding and reasoning. Most important, we conclude that Piaget's analytic tools for discussing spatial development—the distinctions he made among topological, projective, and Euclidean space—are not helpful to an analysis of development.

Despite these problems Piaget made a great contribution to our understanding of development in general and spatial development in particular by recognizing that a developing individual makes use of existing cognitive understandings (beginning from some neonatal starting point) in interpreting (and indeed selectively seeking) environmental and cultural input. Jumping from criticisms of Piaget's hypotheses about cognitive development to the rejection of the constructivist project has been a common move over the past few decades, but failures to support Piaget's very specific empirical hypotheses have narrower implications than are often realized. They do not serve to condemn an interactionist theory in general, especially when the major alternatives, notably radical nativism and simple cultural transmission theory, suffer from far worse problems. We suspect that Piaget might not be distressed to be wrong about egocentrism or to give up thinking about early spatial understanding as topological. His original and central interest was in intelligence as an adaptive characteristic, by which the actions of a child with certain initial endowments within a certain physical and cultural environment can lead to the creation of knowledge.

Nativist Approaches to Spatial Development

Out of the waning of confidence in Piagetian theory came the resurgence of nativism in thinking about cognitive development. Several investigators suggested that spatial understanding may be innately available to infants (most recently, Spelke and Newport 1998). This conclusion has been endorsed in other contexts, for instance, in Gallistel's (1990) discussion of spatial abilities in animals and in Geary's (1995) paper on gender differences in mathematical performance.

At least three kinds of argument and evidence have been taken to support a nativist approach to spatial development. Each argument, however, suffers from empirical flaws or from errors in interpretation or emphasis, as we will discuss at various points in this book but preview here. First, it has been argued that there exists early appearing ability to perform spatial analysis, independent of visual input, as shown by the performance of a young blind child on simple encoding and inference tasks (Landau, Gleitman, and Spelke 1981; Landau, Spelke, and Gleitman 1984). However, this argument depends on study of a single blind child. Other data on spatial inference in blind children suggest very different conclusions, showing spatial development proceeding more slowly than in sighted children—although constructing spatial relations on the basis of nonvisual experience is eventually possible. Overall, the literature on blind children suggests that their spatial abilities increase over time, impressively given their impoverished input, rather than that they possess early mature ability in the absence of relevant input.

Second, it has been argued that understanding space is a modular ability, in the sense of Fodor (1983). In particular, there is said to be a "geometric module" that allows for orientation in terms of the geometry of the environment but that is impervious to information from landmarks in the environment that are noticed and would be helpful. Hermer and Spelke (1994, 1996; see also Spelke 1998) report that young children, following disorientation, rely on the relative position of long and short walls in a rectangular room to find a hidden object, to the exclusion of use of landmark cues such as the fact that one wall is painted blue. In short, the use of geometric information is said to be "encapsulated," modular, and innate. However, this argument is empirically questionable. We have found evidence that when objects truly appear permanently located (a prerequisite for treating them as landmarks), young children do use them to search after disorientation (Learmonth, Newcombe, and Huttenlocher, under review).

Third, it has been argued that biological maturation of specific areas of the brain can account for whatever aspects of spatial development are not accounted for by an innate neonatal start (Diamond 1991). But an appeal to maturation assumes a unidirectional causal path not justified by current knowledge about the role of the environment in neurological development. It is as likely that neurological changes are the product of transactions with the environment as that such changes drive and limit development. In short, the facts uncovered by proponents of nativism are more consistent with an interactionism in which environmental feedback helps to form a plastic nervous system than with a position that relegates environment to the position of a mere "trigger."

Nativists often respond to constructivists (or to environmentalists) by arguing that neonatal starting points are "fundamental" or "foundational," while environmental input, albeit required for normal development, is in some sense secondary. As Carey (1991) writes, these theorists "conjecture that ordinary, intuitive cognitive development consists only of enrichment of innate structural principles" (p. 258). Such claims are matters of emphasis or focus, however, more than statements of fact (see also Overton 1998). If two elements are needed to make a third, one needs to regard both as fundamental, even if one may be more interested in one than the other. If you are lost in the woods and need both an ignition source and dry wood to start a campfire, you would be dismayed to find yourself with only one.

Nativism suffers from an excessive focus on the strength of the origins of cognitive competence, and a relative lack of interest in environmental input and later developmental change. Nativist arguments and empirical work have, however, performed an essential service to the study of cognitive development, by focusing interest on starting points and showing that they are likely considerably more specific and powerful tools than imagined by Piaget or by the classic empiricists.

Vygotskyan Views

A third strand in thinking about cognitive development over the past few decades has been a resurgence of interest in Vygotsky's thinking. Three ideas derived from Vygotsky have been prominent in research involving spatial competence. A first theme is that of "guided participation" (Rogoff 1990), the process by which children come to understand the world better as they are guided by adults or older peers. Investigations of interactions between children and their mothers as the children engaged in copying block designs (Wertsch et al. 1980) and of interactions between children and adults engaged in imaginary errand planning (Radziszewska and Rogoff 1988, 1991) have demonstrated that such guided participation may be an important part of the development of certain spatial skills.

A second thrust of Vygotskyan theorizing has been to stress what is called the situated nature of cognition (e.g., Rogoff and Lave 1984), namely the idea that cognitive effort is uniquely adapted to the demands of particular situations and can be highly specific to those situations. Several demonstrations of situation specificity have involved spatial tasks. For instance, Gauvain and Klaue (1989) found that security guards at the New York Public Library gave much better directions than did librarians, despite equivalent lengths of time on the job and amounts of work-related travel around the building, and Gauvain and Rogoff (1986) found that children's spatial knowledge of an environment was influenced by whether their orienting instructions emphasized learning a route through it or acquiring overall knowledge of the space, including off-route features.

Third, Vygotskyan investigators have focused much interest on the uniquely human ability to deal with symbolic material such as maps or diagrams (e.g., Gauvain 1993, 1995). Thinking about spatial symbol systems naturally focuses attention on the interaction of individuals with their cultural environment, from which such representational systems are acquired. Individual experience is joined with socially guided instruction in the use of invented symbolic systems. That is, students work to understand, and teachers work to transmit, facility with navigational systems, such as studied in the navigational strategies of the Puluwat Islanders (Gladwin 1970; Hutchins 1995) or the use of various mapping conventions (e.g., those involved in rendering the globe as a flat surface). Symbolic systems allow for new knowledge to be gained without direct experience. That is, symbolic systems serve as cultural amplifiers of individual intelligence, as Bruner has long argued.[2]

Research on guided participation, situation specificity and symbolic systems has been an exciting recent area of investigation, serving as a corrective to approaches in which children develop as isolated individuals or in which they develop highly general strategies and understandings. However, focusing only on these themes gives a picture of development that sometimes overemphasizes adult instruction and cultural transmission, ignoring individuals and their own efforts to construct a sensible and coherent world. It seems likely that children interact with the physical environment as individuals as well as participate in social groups. In addition it is important to remember that children often seek out and structure their social interactions, thus giving an individual twist to an apparently social kind of transmission of information. When a child creeps up to watch a weaver at work, the

2. Nativists have often counterargued that cultural transmission depends on biological preparedness (Spelke and Newport 1998). While true, such a point hardly amounts to a denial of the tremendous advantages of *not* having to reinvent the wheel. If each child born in Oceania had to learn anew to navigate, a capacity to develop spatial inference would not allow for much actual inter-island travel, at least not without a good deal of mishap.

individual component is the choice to watch, and the social component is the availability of the guide and whatever demonstrations or advice she offers.

An overemphasis on the role of the social environment in creating and molding individual development is not an inevitable feature of Vygotskyan thinking. Clearly, there can be an important role in the theory for individual children and their sense-making efforts (Rogoff 1990). Most strikingly, Vygotskyan notions of the "zone of proximal development" are quite similar to Piagetian ideas of cognitive readiness. In either case, instruction is geared to the cognitive level of the student. Thus it seems likely that a complete theory of development in any domain must include interactions of the developing child with skilled adults and with a cultural milieu, while avoiding implications that cultural transmission is all of development or that cultural transmission imprints information on a passive organism.

New Thinking about Spatial Development

The goal of the present book is to give an account of how biological preparedness interacts with the spatial environment that infants encounter after birth to create spatial development and mature spatial competence. We begin by presenting a model of mature spatial coding as involving the coding of information with respect to two different possible frames of reference, the viewer and the external environment, as well as the hierarchical combination of information coded at various grains of resolution. We propose that infants begin life equipped with substantial spatial coding abilities, but that experience as to the consequences of using various systems as they observe and move in their environment leads to adaptive changes in the conditions under which each system is used. In addition, by 16 months at least, and perhaps earlier, children have begun to show the hierarchical combination that characterizes adult spatial coding, although the spatial categories they use differ in important ways from those used by adults.

There are other crucial changes in the first few years of life as well. To take just one example, there is a notable shift in children's spatial coding toward the end of the second year as they become capable of coding location using distal landmarks in the external environment. It is possible that this shift is linked to the attainment of a new ability to do more than code and represent spatial information but also to operate on that stored information to solve problems, that is, to do spatial reasoning. Significant developmental change in spatial coding, spatial reasoning and spatial symbol use continues through elementary school as children refine their spatial categories, learn more about how to use symbolic tools such as maps and language, and gain speed and accuracy in capacities such as mental rotation.

The approach to spatial development that we advocate is, in summary, interactionist without being Piagetian. It encompasses nativism by stressing the importance of the starting points for cognitive development in early infancy while denying radical assertions that the competencies present at the beginning are foundational and that subsequent change is no more than enrichment. It encompasses cultural transmission theory by stressing the importance of passing on tools evolved by past generations, especially in the area of graphic and linguistic representations of space, while avoiding the exclusive focus on such transmission sometimes seen in Vygotskyan writing.

Plan for This Book

In discussing spatial representation and its development, it is important to begin by describing the adult state. In chapter 2, we outline a model of spatial coding in directly experienced space, based on prior work and theory. In chapter 3, we review the traditional literature on infant spatial coding, the agenda for which was set by two questions taken from Piaget: whether or not infants begin with egocentric coding of their environment and move to an allocentric coding, and whether or not infants' search behaviors, especially the famous A-not-B error, betray a lack of spatial coding. In chapter 4, we discuss spatial coding during infancy and childhood using the formulation of spatial coding systems presented in chapter 2. We consider the early origins of coding distance in continuous space, of coding location with respect to distal external landmarks, and of hierarchical combination of information. Chapter 5 moves to consider the mental processes that operate on stored spatial information. Here, we discuss the development of abilities to take the perspectives of other viewers, to make judgments of distance, and to perform logical searches in space. Chapters 6 and 7 move away from directly experienced space to consider symbolic space. Chapter 6 deals with spatial information as encoded in models and maps, and chapter 7 considers spatial information as encoded in language. In chapter 8, we summarize the evidence and arguments, and discuss our account of spatial development in relation to various approaches to cognitive development and to other domains of development, including quantitative development, theory of mind, and language acquisition.