The Emerging Spatial Mind

Edited by

Jodie M. Plumert
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DEDICATION

For Tim, Grace, and Will
J.P.

For Larissa, Alekzandr, and Katya
J.S.

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INTRODUCTION

Jodie M. Plumert & John P. Spencer

Human activity and thought are embedded within and richly structured by the space around us. We reach for coffee cups in space. We remember where our keys are in space. We drive our cars to work in space. We talk to one another about space. We draw maps and diagrams of space. We invent devices to help us find our way in space. We think about spaces we can never visit (inside the atom). We think about spaces that are very hard to get to (the moon). Virtually all overt human behavior is spatially grounded and spatially organized. Thus, it is not hyperbole to say that the human mind is spatial.

This volume examines the development of the spatial mind from its humble origins in infancy to its mature, flexible, and (often) skilled adult form. The diversity of research findings and theoretical perspectives in these chapters reflects the upsurge of interest in the development of spatial cognition over the last decade or so. Numerous journal articles have appeared on topics including infants' ability to form spatial categories (Quinn, Cummins, Kase, Martin, & Weissman, 1996; Casasola, Cohen, & Chiarello, 2003), biases in children's memory for location (Huttenlocher, Hedges, & Duncan 1991; Huttenlocher, Newcombe, & Sandberg, 1994; Newcombe, Huttenlocher, Drummey, & Wiley, 1998; Plumert & Hund, 2001; Spencer & Hund, 2003), early language-specific conceptualizations of spatial relations (McDonough, Choi, & Mandler, 2003), and the neural plasticity of spatial abilities (Passarotti et al., 2003; Landau & Zukowski, 2003). An influential authored book on the development of spatial representation and reasoning has also appeared (Newcombe & Huttenlocher, 2000). Despite the plethora of high-quality work on the topic of spatial cognitive development, there have been relatively few attempts to bring this state-of-the-art research together into sharp focus. The last edited volumes on children's spatial cognitive development appeared in the 1980s (Cohen, 1985; Liben, Patterson, & Newcombe, 1981; Potegal, 1982; Stiles-Davis & Kritchevsky, 1988; Wellman, 1985). Thus, the time is right to bring together the exciting recent theoretical and empirical work on children's spatial development into a single, edited volume.

Importantly, however, our goal was not mere aggregation of cutting-edge research. Rather, the rich literature on the emerging spatial mind that has accumulated over the last 30 years sets the stage for considering a central developmental question: *How* do these changes occur? The book tackles this question directly by bringing together the top researchers in the field of spatial cognitive development to provide an in-depth look at candidate processes of change in spatial understanding. Each chapter presents state-of-the-art research and theory organized around two questions: (1) What changes in spatial cognition occur over development? (2) How do these changes come about? More specifically, the authors both describe the developmental changes uncovered in their research and speculate on the processes or mechanisms that lead to these changes. With respect to this latter issue, the authors provide conceptual and formal theoretical accounts of developmental processes at multiple levels of analysis (e.g., genes, neurons, behaviors, social interactions). This strong focus on developmental process makes the book of interest not only to researchers interested in spatial development but also to researchers interested in understanding cognitive change more generally.

The core chapters are organized into three parts: Remembering Where Things Are (part I), Thinking and Talking about Spatial Relations (part II), and Mapping the Neuropsychological Bases of Spatial Development (part III). We selected these three themes because they represent "hot" areas within the field of spatial cognition, areas within which researchers are making serious progress on the question of how spatial skills develop. The four chapters in part I address the issues of how children and adults use metric and nonmetric spatial information to remember previously seen locations (chapters 1 and 2) and to orient themselves with respect to the environment so they can find objects (chapter 3) and navigate effectively (chapter 4). The chapters in part II address fundamental issues of how infants and young children form spatial categories both before and after the onset of language (chapters 6 and 7), how language and thought are intimately linked to the body acting in space (chapters 8 and 9), and how using symbolic representations such as maps constrain (chapter 10) and are constrained by (chapter 9) the development of spatial cognition. The chapters in part III focus on how the absence of a sensory system (chapter 12) or the absence of a set of genes (chapter 13) affects the development of spatial skills and how process modeling of the moment-by-moment dynamics of spatial cognition provides insights into change over longer time scales (chapter 14). Across the entire volume, the authors draw from a rich array of theoretical perspectives to understand developmental change. In so doing, they address fundamental developmental questions regarding relations between qualitative and quantitative change, learning over short and long time scales, and the emergence of function through organism–environment interaction. We highlight and expand on these themes in our concluding chapter.

In addition to the core chapters, each part of the book ends with a commentary written by a researcher outside of the field of cognitive development, but whose research on spatial cognition is closely tied to the focus of the section. To make progress in understanding the nature of cognition, advances must be made in understanding both how cognitive processes operate in mature organisms and how those processes come to be in the first place. One way to achieve this is relatively common: developmental scientists include a group of adult participants in their research to assess the "mature" cognitive system simultaneously with the developing one. This is evident in the many core chapters in this volume that include adult participants in research, from studies of spatial language to studies of spatial memory and navigation. Less common is direct dialogue between developmental scientists and researchers who specialize in adult spatial cognition. The three commentaries are a first step toward such dialogue. The commentators certainly rose to the occasion, effectively relating the research reported in the chapters to contemporary issues in the adult spatial cognition literature, including the problems of selecting frames of reference (chapter 5), bridging internal and external representations (chapter 11), and the mechanisms that underlie spatial cognition across diverse populations (chapter 15). These commentaries identify points of convergence between adult and child research and identify places where developmental research can further inform our understanding of the basic cognitive processes underlying spatial cognition.

We are tremendously excited about the chapters in this volume—the scope and depth of the ideas and research reported here illustrate how far the field of spatial cognitive development has come over the last 30 years. The authors have also tackled difficult developmental questions (and have been willing to stretch themselves a bit), making this volume a rich source of contemporary thinking about developmental process. We are indebted to the authors for their willingness to contribute to the volume and for their patience with the ensuing review process. We are also grateful to the graduate students (both current and former) in the spatial cognition group at the University of Iowa who argued convincingly that an edited volume on spatial cognitive development was sorely needed, as well as to our current and former graduate students for providing additional reviews of the chapters. Our goal in soliciting these reviews was to ensure that the chapters would be accessible both to beginning and to advanced researchers. These reviews were uniformly excellent. In addition, we thank Valerie Vorderstrasse for her invaluable help in putting the book manuscript together.

Finally, we thank our spouses (Tim Barrett and Larissa Samuelson) for their encouragement and support during the many (many, many) hours we spent putting together this volume.

We conclude our introductory comments by asking in what sense the spatial mind can be said to "emerge"; that is, why *The Emerging Spatial Mind*? The concept of emergence reflects the emphasis in this volume on developmental process—that spatial cognitive development is profoundly shaped by children's step-by-step experiences in context. Thus, the structure and content of the spatial mind are not prescribed. Rather, they arise in time via the complex interplay of influences at multiple levels from genes to neurons to behaviors to the behaviors of social groups. The elegant research programs described herein highlight both this complexity and the deep sense in which spatial abilities can be said to "emerge."

The title also captures our sense that the field of spatial cognition is beginning to cohere around an emerging view of the spatial mind. This view integrates not only insights from the field of spatial cognitive development but also insights from research on adult spatial cognition, the neural bases of spatial cognition, the evolution of spatial thinking, and many more. We hope our efforts have contributed to this broader, emerging vision.

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I

REMEMBERING WHERE THINGS ARE

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1

USING SPATIAL CATEGORIES TO REASON ABOUT LOCATION

Janellen Huttenlocher & Stella F. Lourenco

This volume is concerned with spatial development, an adaptively important aspect of cognitive function. Coding the locations of objects and places (food supplies, one's home base, etc.) and being able to use this information to find important locations are critical for humans and other animals. This chapter addresses an important characteristic of location coding, namely, that it is hierarchically organized. At one level, location is specified in terms of distance and direction from stable landmarks (fine-grained coding). At a more general level, location is specified in terms of a region or area (spatial category). The focus of the present chapter is on the role of spatial categories (consisting of regions) in estimating locations that are only inexactly remembered. We also discuss the emergence of spatial categories and their use in estimating location during childhood.

Spatial categories that consist of regions or areas involve two types of information. One type specifies features that are common to instances that are members (see discussion of categories in Smith & Medin, 1981). For example, if a region has a certain climate, and a particular location is in that region, one can infer that the location exhibits that climate. If the region is a desert, all the locations in it will have little rain, influencing the flora found there, and so on. The second type of information in spatial categories specifies the distribution of particular locations in the region. For example, locations might be uniformly distributed over the region, or most locations might be in the northwest quadrant. Information about the distribution may be derived inductively by accumulating data over instances. When locations are clustered in an area and are less dense in surrounding regions, the accumulated information may be used to form a spatial category with boundaries at the edges of the cluster, a central value, and a dispersion around that central value. The notion that categories can be thought of as statistical distributions has been suggested by various investigators (e.g., Anderson, 1991; Ashby & Lee, 1991; Fried & Holyoak, 1984; Homa, 1984). It should be noted, however, that spatial categories need not be inductively based. For example, categories may involve subdivisions of a space separated at axes of symmetry. Such categories may have a presumed distribution; for instance, people may assume they involve uniform distributions of locations.

This chapter focuses on the use of spatial categories to estimate particular locations. Regardless of whether categories are based on inductive or geometric principles, combining category-level information with an inexact fine-grained value can result in more accurate estimation than the use of fine-grained information alone. Accuracy may be increased by using both levels because information in the category indicates where locations are most likely to be. The process of combining information across levels can be modeled as a Bayesian procedure in which prior information is used to improve the average accuracy of estimation. We begin our discussion of this Bayesian procedure by focusing on fine-grained spatial coding. Then we turn to the development of spatial categories and of the hierarchical combination of information at fine-grained and category levels. We also consider the combination of information that is not hierarchically organized, and its role in improving the accuracy of estimation, as well as the origins of information combination in young children and nonhuman animals.

1.1 SPATIAL CODING

Accurate fine-grained coding of the locations of important objects and places is critical to adaptive behavior. It is essential to encode and store target locations in memory sufficiently accurately that the targets can be retrieved later. The coding of spatial locations must enable us to find objects after movement to new locations, even in cases where we are unable to trace our change in position in relation to the target during movement. This problem requires the use of stable landmarks for coding.

1.1.1 Coding in Relation to Landmarks

Coding location in relation to an adjacent landmark simply involves an association between the target and landmark and is not affected by whether there has been movement to a new position. However, when targets and landmarks are not adjacent, location coding involves establishing distance and direction relative to landmarks. Representation in memory of fine-grained information about distance is often inexact. Various factors may contribute to inexactness. One factor is the extent of the distance between a target and a landmark. Coding by eye becomes less accurate as distance increases, as described by Weber's law. Also, location information becomes less exact when visual interference occurs and when time elapses (Huttenlocher, Hedges, & Duncan, 1991). The fine-grained representation of distance may be unbiased even if it is inexact. That is, across a range of accuracy levels, the mean of retrieved values may lie at the true stimulus value, with a normal distribution of uncertainty around this value.

The accuracy of location coding has been shown to improve with increasing age. This increase in accuracy may be due to either or both of two factors: (1) the categories used by older children are more optimal than those used by younger children, as described below (e.g., Huttenlocher, Newcombe, & Sandberg, 1994); and (2) the precision of fine-grained coding itself may increase with age (see chapters 2 and 14).

1.1.2 Self as Landmark

While various types of objects and places may serve as landmarks, viewers themselves are also salient landmarks. An item may be coded as being a certain distance and direction from the self. If the viewer remains stationary, such coding is sufficient for knowing how to find the object. It should be noted that when an object is coded in relation to an outside landmark, it remains critical to know its relation to the self even after movement since this relation is necessary for obtaining the object from one's current location (see Lourenco & Huttenlocher, in press; see also chapter 4).

As noted above, coding an object directly relative to the self is sufficient for finding that object when the viewer remains stationary. It has been claimed that location coding in early childhood is exclusively "ego-centered", such that children relate targets only directly to the self (Piaget & Inhelder, 1948/1967). For example, Bremner and Bryant (1977) presented infants with two identical cloths on a table; an object was hidden under the cloth on one side (e.g., to the infant's right). Then infants were moved around the array by 180°. They continued to search to the right, even when cues marking the correct choice were available (i.e., when one side of the table was painted black and the other side white). These findings showed that infants had coded the target directly in relation to themselves, not in relation to the outside environment. (Note, though, that other work suggests that infants can use the outside environment in coding location [e.g., Acredolo & Evans, 1980; Presson & Ihrig, 1982].)

The relation of a target to the self also can be coded directly, even when movement occurs, if the changing relation to the target is tracked. For example, as a viewer moves relative to an object, the object may go from being in front, to being at the side, to being behind the viewer. However, if a movement has occurred that either could not be or was not tracked, there are two aspects to establishing one's relation to a target: coding that object in relation to stable features of the environment, and coding one's own relation to those stable features. Then the relation between the object and the self can be inferred (e.g., Lourenco, Huttenlocher, & Vasilyeva, 2005).

In many cases, information about a target location is stored in long-term memory. Such information is more likely to involve an association of a target to a particular landmark than an association of a target to a particular viewer position. For example, a frequent location of one's keys may be on the chest of drawers near the door. However, the viewer probably does not have a habitual location relative to the chest, so obtaining the keys involves knowing the position of the keys relative to the chest as well as one's own position relative to that chest. Of course, in some cases, a person does have a habitual position relative to a landmark in a certain spatial context and that position is directly associated with the target object. For example, in a kitchen, the chef may have a habitual location relative to the stove, and the condiments may be in a specific location relative to that stove. In this context, ego-centered coding will be sufficient, and an inference about the relation of the condiments to the self via the stove will not be necessary.

The ability to code a target relative to the self, mediated by the relation of the target to the environment, is seen both in humans and in nonhuman animals. Consider an example from the animal literature. Cheng (1988, 1989) provided evidence that pigeons who learn to find a hidden target (e.g., grain buried in sand) code two kinds of information: the target's relation to nearby landmarks (i.e., landmark-to-target vectors) and their own relation to the landmarks (i.e., self-to-landmark vectors). By coding both the target's relation to landmarks and their own relation to those landmarks, they can (implicitly) compute the distance and direction they must move to retrieve the target (i.e., self-to-target vectors).

1.1.3 The Relation of the Self to Spatial Regions

Spatial coding may also involve locating a target in a particular region. There has been considerable recent work on young children's coding of the location of a target object in an enclosed space that also includes the viewer. The conditions in this work are such that the relation of the target object to the self is not available (e.g., Hermer & Spelke, 1994, 1996; Huttenlocher & Vasilyeva, 2003). A toddler watches a target being hidden in a corner of an enclosure such as a rectangular room. Then the toddler is turned around several times, with eyes covered, to prevent tracking of the relation to the target. Toddlers were found to code the geometric characteristics of a corner (e.g., the longer wall is to the left and the shorter wall is to the right, or vice versa) where the target is located. The geometry of a rectangular room makes it possible to eliminate two of the corners as potential hiding locations, but not to distinguish between the hiding corner and its geometric equivalent. To make this distinction, further information would be required.

In addition to findings showing that a target is coded in relation to space, there is evidence that the viewer's position in relation to the space also is coded: the task is more difficult when the viewer is positioned outside rather than inside the space during the task (Huttenlocher & Vasilyeva, 2003; Lourenco et al., 2005). This finding is clearly inconsistent with the notion that coding is exclusively "environment centered." Cues that relate a target to the outside world do not depend on the viewer's position (cf. Gallistel, 1990). If the position of the self were not involved, the task would not differ in difficulty depending on whether the viewer is inside or outside.

1.2 HIERARCHICAL ORGANIZATION: SPATIAL CATEGORIES

Here we consider spatial categories that specify regions of a space and their function for accuracy in determining the locations of objects. Spatial categories, like categories in general, have boundaries that separate members from nonmembers and also may be characterized by a "prototypic" location that is usually central to the category. In this chapter we consider the role of categories in estimating the locations of particular objects, and here we consider how category information—boundaries and prototypes—may be combined with inexactly represented fine-grained locations in estimation. Combining such information can increase the average accuracy of estimates, as noted above.

1.2.1 Boundaries

In the "classic view," categories are defined by their boundaries; the boundaries specify the necessary and sufficient (defining) conditions for being a member, and all stimuli that fall within the boundaries are equally good members (see Smith & Medin, 1981). It has become widely recognized that there are difficulties with this view since many categories lack clear-cut boundaries. Yet even when boundaries are inexact, they provide the basis for judging whether or not a stimulus is a category member. In philosophical terms, categories are "projectible" (Quinton, 1957). That is, they permit decisions about membership for new stimuli that were never previously encountered. When boundaries are inexact, category judgments are not certain. That is, while it is possible to make decisions about the category membership of new stimuli in these cases, the decisions will be probabilistic.

Boundaries that specify a region that covers a range of locations may have various origins, and differences in origins may be associated with variation in the exactness of boundaries. For spatial categories that are based on distributions of instances (i.e., inductive categories), determining boundaries involves using a set of instances to establish the extreme values of the distribution. Since the boundaries of such categories involve statistical estimation, they will be imprecise to some degree. For spatial categories that are based on geometric principles, such as subdivisions of a larger region along axes of symmetry, the boundaries may be more precisely defined. For example, geometric categories may have boundaries imposed at vertical and horizontal axes of a geometric figure. In addition, spatial categories may be established by convention, such as countries, states, or cities, where the boundaries are exactly specified by legal agreements.

1.2.2 Central Values (Prototypes)

In some cases, categories are appropriately characterized not by boundaries but rather by a "best" or prototypic value. In these cases, categories may have a graded structure; that is, instances may be judged as better or worse depending on their relation to the prototype (e.g., Posner & Keele, 1968). For geometric categories, defined in terms of region shape, the prototype may be the centroid or balance point of the region. For spatial categories defined in terms of a distribution of locations within a region, the prototype is generally the mean or median (i.e., a statistical center). However, it has been noted that best or prototypic category values are not necessarily the central values or means in the category (Barsalou, 1985). For example, an amusement park is a spatial region or category in which the prototypic location that typifies the park may be at the Ferris wheel, even if the Ferris wheel is near the edge of the park.

1.2.3 Using Categories to Estimate Location

As noted above, spatial categories have extent, and targets may be coded as having locations within them, specified by distance from corners or edges, and so on. It is well known that categories can affect the judgment of stimuli. When stimuli are remembered only inexactly, people tend to make biased judgments, reporting stimuli as more similar to a central value than they really are. We have proposed a model that explains category bias in estimating inexactly remembered stimuli (e.g., Huttenlocher et al., 1991). The idea of this model is that category information is used to construct an estimate that best reflects the true stimulus value. As in Bayesian statistics, prior (category) information is incorporated in forming estimates of stimuli that are inexactly remembered. While this process of integrating hierarchically organized information introduces bias in individual estimates by moving them toward category centers, it improves average accuracy by reducing the variability of the estimates. The inexactness of memory for particular locations determines the extent of the adjustment that will most increase the accuracy of estimates.

The intuitive logic behind the use of categories in estimation is that if one is unsure about the value of a particular stimulus, it is advantageous to use prior information about the distribution of stimuli in the category in making an estimate. The weight that should be given to prior information versus a fine-grained value depends on their relative variability. The less certain the information about a fine-grained value, the more important the category. When there is no information about the fine-grained value, and one is forced to guess, one should opt for the category mean. When the instances in a category are more dispersed, the category is less important. Indeed, when the category instances are maximally variable, the category may not contribute noticeably to accuracy, so it may be just as well to use fine-grained information alone.

The weight that should be given to category information to maximally increase accuracy depends on the relative uncertainty of fine-grained and category information at the time an estimate is made. The logic is that the degree of uncertainty of the fine-grained value at this time point is what determines how best to weight category information to maximize accuracy. If there were no uncertainty at the time of estimation, there would be no gain from category information. In general, the importance of category information is greater when less is known about the location of a particular stimulus at the time of estimation.

Here we describe the processes by which fine-grained and category information can be combined and the effect on the accuracy of location estimates. These processes operate on inexact stimulus representations; they include truncation due to category boundaries and weighting with a central value. These processes have been treated in detail in several articles (e.g., Engebretson & Huttenlocher, 1996; Huttenlocher, Hedges, Corrigan, & Crawford, 2004; Huttenlocher, Hedges, Lourenco, Crawford & Corrigan, in press; Huttenlocher et al., 1991; Huttenlocher, Hedges, & Prohaska, 1988; Huttenlocher, Hedges, & Vevea, 2000) and are discussed below.

1.2.3.1 TRUNCATION The precision of boundaries is important for the accuracy of estimates. If category boundaries are exact, it is possible to prevent misclassifications of inexactly remembered stimuli near those boundaries by truncating values that lie outside the boundaries. Suppose, for example, that one has encountered a set of stimuli covering a range of locations. In recalling an inexactly represented location that is known to be in a particular region, one may nevertheless retrieve a value that is outside the boundary of that region. That value may be rejected as wrong and another value sampled. The rejection process will result in bias in individual estimates because truncation will eliminate part of the distribution of inexactness. However, if the categorization is correct, average accuracy will be increased by eliminating errors.

With precise boundaries, truncation leads to a distinct pattern of bias. Figure 1.1 shows a location near a boundary, together with information as to what happens to the distribution for that location after truncation (based on values inside the boundary). The estimated location will be farther from the boundary than the true value because of rejection of values recalled as outside that boundary. Bias will be greater for a location nearer the boundary because the portion of the distribution of inexactness that overlaps the boundary, and hence is eliminated, will be larger. The top panel in figure 1 shows a stimulus near the boundary, with overlap and bias in reported values. The bottom panel in figure 1 shows the pattern of bias for different stimulus values in the region of that boundary resulting from truncation. It shows the shape of the curve resulting from rejection of values lying at various locations outside that boundary; bias is greatest near the boundary

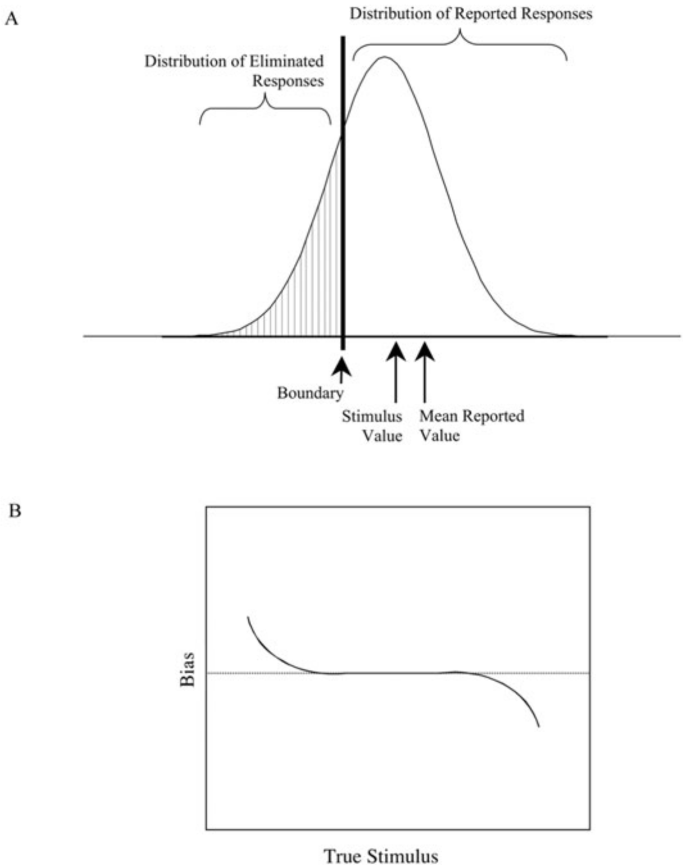

Figure 1.1 How truncation leads to bias in estimation for a particular stimulus value (*top panel*), and the bias it produces (*bottom panel*).

and decreases rapidly with increases in distance from a boundary. Truncation effects at a particular location will be larger when the uncertainty of that location is greater. Truncation can occur when boundaries are somewhat inexact, but the effect will be less marked than with exact boundaries.

1.2.3.2 WEIGHTING WITH A CENTRAL VALUE Average accuracy also can be increased by combining an inexact fine-grained value with a prototypic central value. That is, if a particular location is remembered only inexactly, weighting it with a central location in the region can improve average accuracy. Weighting an inexact stimulus with a prototype leads to a distinctive pattern of bias. That bias will be linear across the category if stimuli are equally inexact. However, if the representation of stimuli in the category is differentially inexact, the bias will be greater for those stimuli that are represented less exactly.

In a geometric form such as a circle, people tend to divide the overall shape into regions. In particular, there is evidence that they impose vertical and horizontal boundaries, forming quadrants. In a circle, they code particular locations using polar coordinates (i.e., angle and distance from the center of the circle). The evidence comes from Huttenlocher et al. (1991). In this study, people were shown a display with a dot in a circle, and the display was then removed; the distribution of instances presented was uniform across the circle. The participants then reproduced the location of the dot shortly after the original stimulus disappeared. Dots were systematically misplaced toward the central value within each quadrant (i.e., the centroid), as shown in figure 1.2. This pattern of data would be understandable if people imposed vertical and horizontal boundaries on the circle and treated the centroids of the quadrants as prototypes, weighting this category information with an inexact fine-grained value in estimating location.

Inexactness of stimuli affects how category information should be weighted relative to particular values to maximize accuracy. Category information should be weighted more heavily when the fine-grained stimulus value is less exact and also when that category information is more exact (i.e., when the boundaries are more precise or when the dispersion of instances around the prototype is less). The greater the weight of the prototype relative to the inexactness of fine-grained information, the more a stimulus should be moved to the center. Huttenlocher et al. (1991) tested this claim by varying the degree of uncertainty of particular locations. People reproduced the location of a dot either immediately following the removal of the original display or after completing a visual interference task. Responses were more biased toward the center of the categories for the interference condition than for the noninterference condition. That is, with greater uncertainty about location, category information was weighted more heavily relative to memory for specific locations.

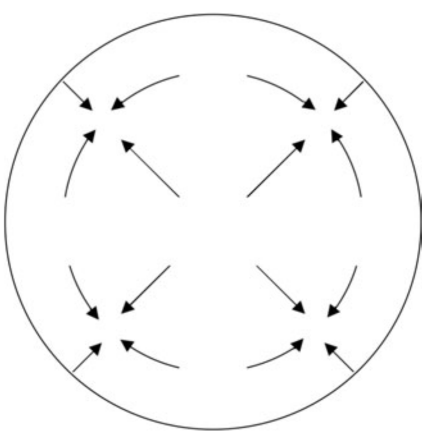

Figure 1.2 The pattern of bias found when people were asked to reproduce the location of dots from memory.

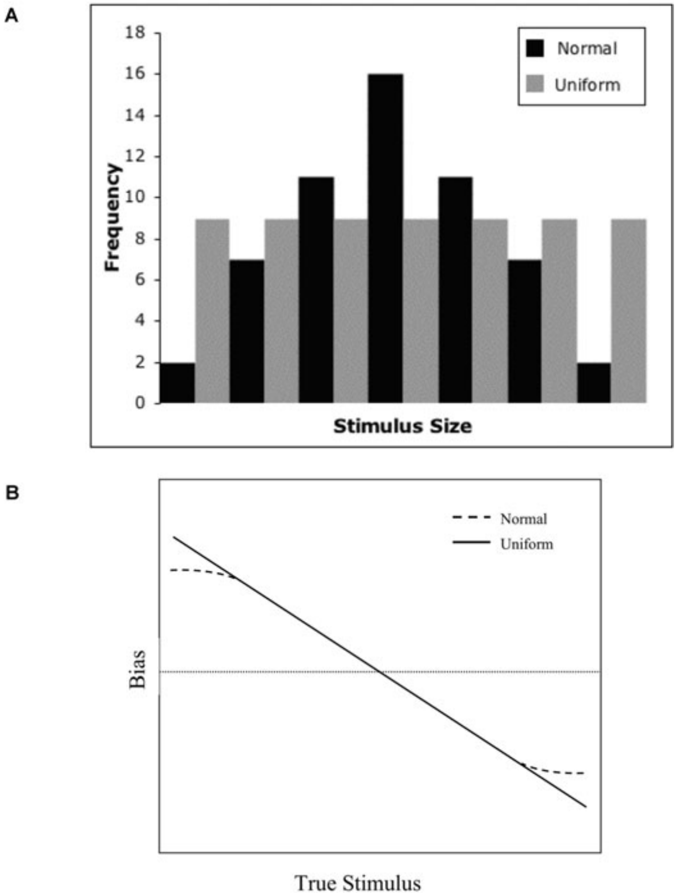

Figure 1.3 (*Top panel*) Uniform versus normal distribution of stimuli. (*Bottom panel*) Mean response bias in the uniform and normal conditions; positive values (*above bias line*) represent overestimation of stimuli, and negative values (*below bias line*) represent underestimation.

Dispersion of instances in the category (prototype uncertainty) also should affect the weighting of category information. While we have used uniform distributions in our research with circular spaces, it would be possible to use uneven distributions. This might affect estimation because, other things being equal, the more concentrated instances are near a category center, the more an inexact value should be adjusted toward that center. Huttenlocher et al. (2000) examined judgments of length and found that when people were presented with stimuli from categories with different distributions, normal versus uniform, bias was affected. The bias curve was steeper in the central region of the category for the normal distribution where the lengths of items were clustered than for the uniform distribution where the lengths were evenly spaced. From the standpoint of rational behavior, this is because the likelihood that the uncertain value is near the center is greater for normal distributions. Further, there was less bias near the edges in the normal than in the uniform condition. Presumably, this is because there are fewer stimuli near the edges for the category in the normal distribution, so the boundaries induced from the observed stimuli will be more uncertain, and not all instances will be classified as members of the category. Adjustment to the category center occurs only for instances that have been classified as members (see, e.g., figure 1.3).

1.2.3.3 TRUNCATION AND PROTOTYPE WEIGHTING TOGETHER Both boundary and prototype effects on a single task were reported by Engebretson and Huttenlocher (1996). They presented people with a display that showed a line in a particular orientation in a frame that was in the shape of either a V or an L. People then were asked to reproduce a line's orientation in a blank frame. They did so either immediately following the removal of the display frame or after an interference task. People tend to impose a boundary in such cases, subdividing a space into equal subregions (vertical boundary for the V frame and diagonal boundary for the L frame). Comparison of lines in the different frames showed that people made fewer category errors with the V than with the L frame. One finding was that people in the interference condition showed more bias toward an angular prototype in the center of each category, indicating that the weighting of categorical information increased as fine-grained certainty decreased (see also Huttenlocher et al., 1991; Spencer & Hund, 2002). For the V frame, the imposed boundary is at the vertical, which is more precise than a diagonal boundary (e.g., Wenderoth, 1994). Another finding was that, with the V frame, but not with the L frame, there was truncation at the axis separating two categories, in addition to weighting with a prototype. Truncation would be expected with a V frame since the axis of separation was at the vertical, which is the most exact boundary.

1.2.3.4 CATEGORY ADJUSTMENT AND DISTANCE JUDGMENT Thus far, we have focused on category effects on estimation of the location of a single stimulus. The model also has implications for bias in the estimation of distances between stimuli. Two inexactly represented stimuli from the same category both will be adjusted toward the center, so the distance between them will be underestimated. When two stimuli are from adjoining categories, they will be adjusted toward the centers of their respective categories, with the nature of the bias depending on the locations of stimuli. That is, if the stimuli lie near the boundary of separation between the categories, the distance will be overestimated because both stimuli are adjusted toward the centers of the categories they are in. However, if the stimuli lie near distal boundaries, adjustment toward the centers of the respective categories will lead to underestimation of the distance between the two stimuli.

Categories also give rise to asymmetries in estimates of the distance between a pair of stimuli depending on the direction in which they are compared. Such asymmetries arise because the extent to which stimuli are adjusted depends on their locations in a category (e.g., McNamara & Diwadkar, 1997; Newcombe, Huttenlocher, Sandberg, Lie, & Johnson, 1999; A. Tversky, 1977). Bias is greater when a stimulus is farther from the center and nearer to the boundary. Consider the estimated distance between two items in a category when one item is near the center and the other is near a boundary. The task involves indicating the location of one item (the target) relative to a fixed item, thus implicitly estimating distance between the two. When the center item is fixed, distance will be underestimated because a target near the boundary will be moved to the center of the category by prototype weighting, and in some cases, by truncation as well. In contrast, when the item near the boundary is fixed at its true location and the one near the center item must be placed, there will not be a corresponding underestimation of distance because there will not be much adjustment for an item near the center. Thus, categories may result in judging the distance between two locations as different depending on the direction of comparison. While such asymmetries of judgments may sound irrational, in the context of our model, they are part of a general mechanism for estimation that *is* irrational, increasing the overall accuracy of estimates.

1.2.4 The Choice of Which Categories to Use

Thus far, we have discussed the use of spatial categories in estimating location without considering why people might use one way of organizing a space into a particular set of categories rather than some other set of categories. Nor have we discussed whether differences in the particular category scheme used may affect accuracy. We have noted that spatial categories can be based on a priori geometric information (e.g., the quadrants of a circle) or induced from a set of exemplars. We have shown that with uniform presentation of instances in a circle, people tend to form geometric categories. However, one could present uneven distributions of instances instead. Then one might expect that people would form inductive categories with boundaries in low-density regions and prototypes in high-density regions. For example, one could make the density of instances greatest at the vertical and horizontal axes of a circle, with few instances at the diagonal axes. Other things being equal, it would be advantageous in this case to form categories with the vertical and horizontal axes as prototypes and the diagonal axes as boundaries. Huttenlocher et al. (2004) attempted to induce categories with prototypes at the vertical and horizontal axes (see figure 1.4). Participants did not alter their geometric categories; rather, responses in all conditions remained biased toward the centers of quadrants defined by vertical and horizontal axes (see figure 1.4, bottom right). In other cases, however, people do alter their categories when the distribution of instances is varied (see, e.g., Spencer & Hund, 2002).

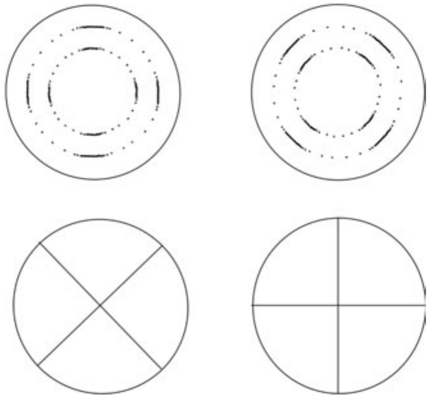

Figure 1.4 The *top row* shows the distribution of dots, and the *bottom row* shows the categories. The *left column* represents the case with clusters at the vertical and horizontal axes. The *right column* represents the case with clusters at diagonal axes.

Let us consider why people in our study might use geometric categories rather than inductive categories centered at the regions of high density. The question might be raised of whether, in these cases, people are using nonoptimal types of estimation. We argue that, actually, the greatest accuracy of estimates may be achieved by the use of geometric categories in which the distribution of stimuli is ignored. The reason is that accuracy of estimates is increased by assigning stimuli to the correct category. Assignment to the wrong category leads to large errors because adjustments will be made in the wrong direction. As noted above, Engebretson and Huttenlocher (1996) showed that people make more errors in category assignment for a boundary at the diagonal axis than for a boundary at the vertical axis. The larger proportion of category errors when boundaries are at the diagonals may outweigh the greater accuracy involved in using density information. Hence, a possible reason why a priori categories would be favored over inductive categories in circular regions with uneven distributions is that they maximize average accuracy because of the greater precision of boundaries. This finding suggests that the potential effects of boundary locations on accuracy of estimation may be incorporated into decisions about what categories to use.

1.2.5 Hierarchical Coding in Animals and Children

It has been shown that rhesus monkeys, like adult humans, use multiple information sources involving hierarchical coding of location (Merchant, Fortes, & Georgopoulos, 2004). With a modified version of the Huttenlocher et al. (1991) paradigm, Merchant and colleagues found that monkeys use fine-grained and categorical information to estimate location, with categorical prototypes being given more weight at longer delays. Recall that Huttenlocher et al. (1991) found that adults divide circles into categories consisting of quadrants, using two dimensions—angle and radius. However, Merchant et al. (2004) found that rhesus monkeys used categorical prototypes involving mostly the radius. That is, if a circle is categorized based

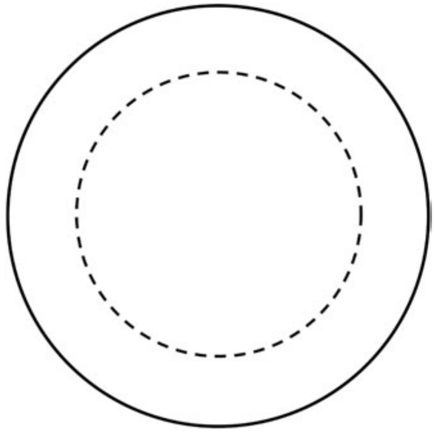

Figure 1.5 An example of radial categories.

on radial information, the prototypic locations toward which uncertain locations are adjusted would lie on a circular line that divides the circle into two regions of equal area (see figure 1.5).

Hierarchical coding involving a single dimension also occurs in young children, as shown in several studies (e.g., Huttenlocher et al., 1994; Sandberg, Huttenlocher, & Newcombe, 1996). The development of hierarchical spatial coding was first investigated by Huttenlocher et al. (1994) using a task in which children searched for a toy hidden in a long narrow sandbox. At least by 16 months, children were shown to have coded both fine-grained and category information. Their mean responses for each true location were biased toward the center of the sandbox; the children treated the sandbox as a single category with boundaries at the perimeter and the prototype at the center. Older children subcategorized the space, dividing the box into two halves with prototypes at the center of each. Division of a space along a single dimension into multiple categories was shown to emerge at different ages for spaces of different sizes. Specifically, 4-year-olds subdivided a small rectangle on a sheet of paper into two categories, but treated the large sandbox as a single category.

Sandberg et al. (1996) subsequently investigated the estimation of location in the circle task used by Huttenlocher et al. (1991). They showed that 5- to 7-year-olds, like the rhesus monkey tested by Merchant et al. (2004), used only one of the dimensions: radial distance. The adult pattern, where both angle and radius were coded hierarchically, was observed only at 9 years of age.

1.3 NONHIERARCHICAL ORGANIZATION: OTHER CASES OF INFORMATION COMBINATION

The research we have presented shows how the combination of multiple sources of information—fine-grained and categorical—increases accuracy in estimating location. In this and the following section, we show other combinations of multiple information sources that increase accuracy of estimation, even when those sources are not hierarchically organized. For example, as indicated below, the width of an object can be estimated using either visual or haptic (i.e., touch) sources of information, or these two information sources (visual and haptic) can be combined in constructing an estimate of object width. Combining the information from two sources also may increase average accuracy of estimation. In a problem where each source of information is uncertain (i.e., there is variability), combining information from the different sources can reduce variability, leading to greater accuracy of estimation.

It is possible to use multiple location cues that are not hierarchically organized. For example, we have indicated that coding of a target location may be based on the target's position relative to the self or its relation to outside landmarks. It is possible to combine such information sources in estimating location. There is emerging evidence that combining information about an object's relation to outside landmarks and to the self may occur in both children and animals. It also should be noted that with outside landmarks, there is more than one possible source of information; for example, a target could be coded in relation to both proximal and distal landmarks (e.g., Kelly & Spetch, 2001).

If the information from different sources in memory were exact, use of more than one source could not improve accuracy. However, the information in memory is rarely exact. With inexact coding, combining information from different sources can result in a more accurate estimate. In such combinations, more precise information should be weighted more heavily than information that is less precise. There is evidence that humans combine visual and haptic information in a nearly optimal fashion (e.g., Ernst & Banks, 2002; Gepshtein & Banks, 2003). Ernst and Banks (2002) had subjects judge the width of stimuli that were presented visually, haptically, or bimodally. The variance of judgments based on unimodal stimulus information was greater than the variance of judgments based on combined bimodal information (visual and haptic). To best increase accuracy, the weight given to the information that is less variable should be greater than the weight give to the information that is more variable. Vision is often more reliable than haptic information, and in these cases it is weighted more heavily. However, Banks and colleagues found that when visual information is less reliable, people place greater weight on the haptic information. Note that different sources of information may come from the same modality and may be combined to improve accuracy; for example, stereo and texture cues in the visual modality can be combined to increase accuracy (Knill & Saunders, 2003).

There are contexts in which combining different information sources does not necessarily improve the accuracy of estimates. If one or more cues are highly variable, their use may fail to increase accuracy of estimation. Indeed, using multiple cues may constitute an "overfitting" of the available information, in which case the use of multiple information sources may actually reduce accuracy (Gigerenzer, 2000). In this case, it would be best to ignore one of the cues. That is, even when multiple sources are available, it is possible that the optimal strategy could be the "take the best" strategy of using what is most reliable and ignoring other information. Indeed, there are cases where people and animals use only one cue and ignore others.

In the discussion of spatial coding above, we described similarities in location coding across a broad age period as well as across a broad range of species. Let us consider what is known about the similarities across age and species in combining information from multiple sources. Since combining information from different sources can increase the accuracy of estimates, it is of interest to determine whether such a process occurs across age and species.

There are several examples where multiple cues that are not hierarchically related are used by nonhuman animals for estimating location (rats: Whishaw & Tomie, 1997; pigeons: Cheng, 1988; ants: Wehner & Srinivasan, 2003). For example, small mammals combine information about landmarks with information about distance and direction of path (i.e., dead reckoning). Normally, when landmark and path information are not very discrepant, precedence is given to the landmark. However, when landmarks are moved so that landmark and path information are highly discrepant, rats place more weight on the path information, using path information to determine the target's location (Whishaw & Tomie, 1997).

In other cases, animals may use only one information source, ignoring others altogether. As indicated above, cues may be ignored because they are highly variable or biased. This strategy for estimating location has recently been shown experimentally with rats. Shettleworth and Sutton (2005) trained rats to forage in a large arena with their home cage placed at the edge of the arena. The home cage was marked by a prominent beacon that hung over the entrance. In cases when the beacon was shifted by 45° from its usual position, rats continued to rely on the beacon for homing. However, with more substantial shifts of 90°, the beacon was ignored and the rats relied instead on path integration. In neither case did the animals use a combination of cues. Instead, they chose one form of location coding over the other.

Another situation where a single cue is used to the exclusion of other information concerns the disorientation task discussed above, in which children have been shown to code the geometry of an enclosed space (e.g., Hermer & Spelke, 1996). The task was originally developed by Cheng (1986) for use with rats. Cheng showed that, when prevented from keeping track of their movements, rats used the geometry of a rectangular enclosure to locate a target hidden in one of the corners. That is, after disorientation, rats divided their search between the two geometrically appropriate corners (i.e., the correct corner and the corner diagonally opposite to it). When nongeometric landmark information was available to distinguish between the geometrically equivalent corners, rats ignored it, continuing to search solely on the basis of geometry.

While it has been found that young children rely exclusively on geometric information to determine the location of an object hidden in a small enclosure (Hermer & Spelke, 1994, 1996), exclusive use of geometry does not occur in larger spaces (see chapter 3). Although, in a small room, children failed to incorporate information about nongeometric features (i.e., a blue wall), they used both types of information in a larger room (Learmonth, Nadel, & Newcombe, 2002; Learmonth, Newcombe, & Huttenlocher, 2001). These findings suggest that geometric and nongeometric information may be combined in a weighted fashion. Geometry may be privileged because it is more stable across time than is nongeometric information (see Gallistel, 1990). Whether or not nongeometric landmark information is combined with geometry may depend on the ecological validity of nongeometric features; for example, larger features may be more stable and hence more reliable (Cheng & Newcombe, 2005). Further, a variety of mobile animals give more weight to nearer than to farther landmarks in estimation (bees: Cheng, Collett, Pickard, & Wehner, 1987; humans: Spetch, 1995), consistent with Weber's law in which smaller distances would be coded more accurately than larger distances (Cheng, 1992).

1.4 SOURCES OF DEVELOPMENTAL CHANGE IN CATEGORY USE

In this chapter, we have discussed the use of multiple sources of information in estimating particular locations. We have focused on category information, discussing how spatial categories are used in conjunction with inexact fine-grained stimulus values in the estimation of location. Spatial categories in this context can be specified in terms of statistical information concerning the distribution of instances across some region of space. (The distribution can be either inductive, based on a set of instances, or noninductive, based on a presumed distribution of instances.) The notion of adjusting fine-grained values using category information to increase the accuracy of estimation can be likened to Bayesian procedures in statistics. Use of Bayesian procedures involves complex processes. That is, people must form categories that specify boundaries, prototypes, and dispersion of instances around those prototypes. Then they must use these categorical structures in conjunction with fine-grained values to construct stimulus estimates. However, people are unaware of coding different levels of information and combining them to form estimates. They believe that they simply recall stimuli, even though their behavior indicates that they have used Bayesian-like adjustment processes.

There are two different interpretations of why adjustment processes might be automatic and unconscious in adults. The first is that these adjustment processes emerge from earlier explicit reasoning strategies based on statistical principles; processes that combine information across levels may then become automatic because they are used so frequently. However, there is reason to favor an alternative, which holds that the tendency to form categories and combine the category information with fine-grained values constitutes a basic cognitive framework for estimation that is available early in life. The evidence arises in studies that show that, although using categories in estimation involves complex processes, these processes are seen in children as young as 16 months and in nonhuman animals. Given the adaptive importance of accuracy in estimation, it would seem reasonable to suppose that Bayesian-like procedures would have arisen in the course of evolution.

To posit that Bayesian procedures predate experience is quite different from positing innate availability of notions about states of affairs in the world, as in recent claims in the literature. The notion that certain assumptions about the world predate experience and are available from the start of life has been referred to as "core knowledge" (Spelke, Breinlinger, Macomber, & Jacobson, 1992). An example of core knowledge is the notion that objects only remain suspended when supported. Even though the word "knowledge" generally refers to beliefs that are true—that correspond to actual states of affairs in the world—claims such as this one about support might or might not correspond to the world (i.e., they could be either true or false). Clearly, the notion of support is a contingent one that could be either true or false, since one can imagine a world in which objects might remain suspended without support.

Thus, there are important differences between positing Bayesian-like principles, which are not beliefs, as innately available versus positing core knowledge, which concerns content, as innately available. Bayesian procedures are reasoning processes that improve average accuracy and are applicable across domains in cases where instances can be accumulated and used in estimation of inexactly remembered stimuli. Since accuracy of estimation is adaptively important, it is reasonable that such processes might be part of the inherited endowment of both human and nonhuman animals.

Regardless of the origins of estimation procedures, there clearly are important developmental changes in categories and their uses over age. The use of imposed boundaries to subdivide a space emerges only gradually. The experiments we have described show age-related changes in whether and how geometric forms are subdivided. For circles, younger children's categories involve just one dimension (radius), whereas the categories of older children and adults may involve two dimensions (radius and angle). For single-dimensional categories, toddlers do not divide the space, but rather form a single category with a prototype in the center; in contrast, older children subdivide the space into more than one category, with prototypes at the center of each category. These developmental changes would seem to reflect an increasing ability to impose complex categorical structure on a space.

Finally, certain spatial categories can only be formed by creatures that possess the ability to interpret symbols such as maps and spatial language, and the processes used in reasoning about these categories may be complex. For example, constructing spatial categories such as "peninsula" or "island" requires symbolic skills. The ability to subdivide such categories may involve different skills than the subdivision of geometric forms. Generally speaking, such categories will not be symmetric or simple, like circles or rectangles. There is evidence to suggest that irregular shapes based on maps may be schematized in terms of simple geometric figures, and the spatial relations among such categories may be schematized in terms of simple spatial relations such as "above" or "next to" (e.g., Stevens & Coupe, 1978; B. Tversky, 1981). Such schemata can aid accurate judgments of direction among instances but can also lead to bias. For example, in judging the spatial relation between two cities in different states, a simple east–west relation will generally support correct inferences, such as that Las Vegas is east of San Diego. However, the simplification of the category structure will lead to error, such as that Reno also is east of San Diego (Stevens & Coupe, 1978; B. Tversky, 1981). Let us conclude by noting that the study of such categories and reasoning processes, while beyond the scope of this chapter, also are topics that concern the use of spatial categories in reasoning about location.

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