

- Tversky, B. (1981). Distortions in memory for maps. *Cognitive Psychology*, 13, 407–433.
- Wehner, R., & Srinivasan, M. V. (2003). Path integration in insects. In K. J. Jeffery (Ed.), *The neurobiology of spatial behaviour* (pp. 9–30). Oxford: Oxford University Press.
- Wenderoth, P. (1994). The salience of vertical symmetry. *Perception*, 23, 221–236.
- Whishaw, I. Q., & Tomie, J. A. (1997). Perseveration on place reversals in spatial swimming pool tasks: Further evidence for place learning in hippocampal rats. *Hippocampus*, 7, 361–370.

 2

ORGANISM–ENVIRONMENT INTERACTION IN SPATIAL DEVELOPMENT

Explaining Categorical Bias
in Memory for Location

JODIE M. PLUMERT, ALYCIA M. HUND,
& KARA M. RECKER

In his book *The Ecological Approach to Visual Perception*, James Gibson introduced the notion of an affordance:

The affordances of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or for ill. The verb *to afford* is found in the dictionary, but the noun *affordance* is not.

I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment.

(J. J. Gibson, 1979, p. 127)

A critical concept here is the complementarity of the organism and environment. In other words, possibilities for action depend on *both* the characteristics of the organism and the structure of the environment (e.g., water offers a surface of support for a water bug but not for a human). Within the ecological perspective, this concept of the mutuality between the organism and the environment has mainly been applied to understanding perception and action (e.g., Adolph, 2000; E. J. Gibson & Pick, 2000; Lockman, 2000; Plumert, Kearney, & Cremer, 2004; Rieser, Pick, Ashmead, & Garing, 1995; Warren, 1984). Thus, changes in the environment and changes in the organism (or both) lead to changes in possibilities for action. For

example, Karen Adolph and her colleagues (Adolph, 1997, 2000; Adolph, Eppler, & Gibson, 1993; Eppler, Adolph, & Weiner, 1996) have shown that toddlers' decisions about whether to descend a slope depend both on walking skill (a characteristic of the organism) and on the steepness of the slope (a property of the environment). Changes in walking skill and changes in the steepness of the slope fundamentally alter the interaction between the perceiver and the environment, leading to changes in possibilities for action. In this chapter, we expand this view of perception/action to the domain of cognition: perceiving, acting, and *thinking* emerge out of the interaction of the characteristics of the organism and the characteristics of the environment. Moreover, we argue that this view of organism–environment interaction provides a particularly good framework for conceptualizing how spatial thinking emerges over time.

The chapter is divided into three sections. First, we outline our general theoretical approach and its implications for understanding spatial development. We then provide examples from our own work to illustrate how bias in memory for location emerges out of the interaction of the structure available in the task and the characteristics of the cognitive system. We conclude with thoughts about why we need the concept of organism–environment interaction to understand change over both short and long time scales.

2.1 THE THEORETICAL FRAMEWORK

What does it mean to say that spatial thinking (or any kind of thinking) is a joint function of the characteristics of the organism and the structure of the environment? Put simply, thinking emerges out of interactions between the organism and the environment that take place in the context of solving problems. Thus, to fully understand any behavior both in the moment and over development, we cannot simply examine the characteristics of the organism or what the environment offers the organism. Rather, we must understand how the two *interact* at any given point in time and how these organism–environment interactions change over time. This view necessarily implies that thinking (like perceiving and acting) is a dynamic process in which changes in the organism or the environment (or both) alter the nature of the interaction, resulting in changes in thinking. From this perspective, cognition is not something that sits in the head of the organism. Rather, thinking is an emergent product of a system that includes both the organism and the environment.

An important consequence of this view is that neither the organism nor the environment has causal priority for explaining behavior either in the moment or over development. Organisms cannot perceive, move, or think independent of environmental structure, and environmental structure has no meaning independent of the characteristics of the organism. In ecological terms, organisms use the available information in the environment to guide thinking, but what is “available” is constrained by the characteristics

of the organism. Thus, the functional value of environmental structure is constrained by the cognitive system (e.g., information-processing skills and background knowledge). Likewise, information-processing skills and background knowledge can only function in the context of environmental structure. In a nutshell, thinking can only happen as the organism and the environment work together as a unified system. Like possibilities for action, possibilities for thought (e.g., solutions to problems) are created in the moment based on what the cognitive system and the environment bring to the table. This necessarily means that we need to understand both the characteristics of the cognitive system (an endeavor traditionally left to the field of information processing) and the structure available in the environment (both physical and social) for guiding thinking.

What are the implications of this view for understanding changes in spatial thinking over developmental time scales? From an ecological perspective, the key to understanding developmental change is to specify how experience leads to changes in the organism–environment interaction (E. J. Gibson, 1988; E. J. Gibson & Pick, 2000). Like Piaget's concepts of assimilation and accommodation or Vygotsky's ideas about scaffolding and the zone of proximal development, this view suggests that there is a cyclical quality to organism–environment interaction over both shorter and longer time scales. That is, changes in the organism lead to changes in the information that is available, thereby allowing the organism to experience the environment in a new way. In turn, these new experiences lead to further changes in the organism at both neural and behavioral levels. Thus, interaction with environmental structure is necessary to produce changes in the organism, but the structure that is “available” (i.e., can be experienced) is constrained by the characteristics of the organism. In the past, research from an ecological perspective has focused on how changes in the action capabilities of the organism lead to changes in the amount or type of perceptual information that is “available,” and how experiences with using new perceptual information to guide action lead to further changes in the organism (Adolph, 1997; J. J. Gibson & Gibson, 1955). We argue that this developmental framework is also relevant for thinking about how cognitive change occurs. In particular, changes in cognitive skills (e.g., attention, memory, or strategy use) lead to changes in the amount or type of information that is available for solving specific problems. Experience using new information to solve specific problems leads to further changes in cognitive skills. For example, experience using salient environmental structure (e.g., physical barriers that separate locations into regions) to organize searches for objects may lead to improvements in children's spatial clustering strategies. In turn, these improvements in spatial clustering strategies might allow children to exploit more subtle environmental structure (e.g., perceptual boundaries that separate locations into regions) to organize their searches for objects. As this example illustrates, the developmental changes we see in children's spatial thinking come about through recurrent organism–environment interactions

that alter how the cognitive system interacts with environmental structure to solve everyday problems.

We now turn to considering empirical examples of organism–environment interaction drawn from our own work on the development of spatial memory. The goal here is to provide examples of how one must simultaneously consider both what the child (or adult) brings to the situation and what the environment provides in order to construct a coherent account of the processes underlying thinking in the moment and changes in thinking over time. Although the ecological approach emphasizes the importance of studying how organisms solve problems in everyday environments, we focus on problem solving in small-scale laboratory tasks designed to capture important aspects of the real world such as perceptually salient boundaries and spatially organized experience. Note that we draw both from concepts about the characteristics of the cognitive system from mainstream information-processing approaches and from ideas about the structure of the environment from a traditional ecological approach. We believe that this admittedly unconventional wedding of the two approaches leads to a much richer picture of spatial thinking and development than does either one alone.

2.2 EMPIRICAL EXAMPLES OF ORGANISM–ENVIRONMENT INTERACTION: CATEGORICAL BIAS IN MEMORY FOR LOCATION

Imagine you are a child who has “borrowed” your sister’s toys to play with while she is away visiting a friend. Now, your task is to put those toys back exactly where they were before so that she will never notice that they have been touched. How do you accomplish this? From a traditional information-processing perspective on spatial memory, the accuracy and bias of your placements depend solely on how the cognitive system codes, maintains, and retrieves spatial information. We argue that this perspective reflects only half of the story (i.e., the part about what is in the head of the organism). To provide a complete description of how people reproduce locations, we need to consider how the processes of coding, maintaining, and retrieving spatial information are intimately linked to environmental structure. In the pages that follow, we illustrate the importance of organism–environment interaction for understanding the development of spatial thinking using our program of research on how children and adults reproduce sets of previously learned locations. These studies clearly show that it is impossible to predict bias in placements by referring to age or task structure alone. Rather, variations in how the same age group responds to different task structures and how different age groups respond to the same task structure suggest that biases in location estimation emerge out of the interaction of the cognitive system and environmental structure.

Our basic task involves a learning phase and a test phase. Participants first learn the locations of 20 miniature objects marked by dots on the floor of an open, square box (approximately 3 ft long × 3 ft wide × 12 inches

high) placed on the floor of a laboratory room (see figure 2.1). We typically provide structure during learning (e.g., boundaries subdividing the box into quadrants) so that the locations are organized into four groups of five locations. Participants first watch while the experimenter names the objects and places them one at a time on the dots until all 20 objects have been placed. The experimenter then gives the objects to the participants one at a time and asks them to try to place them on the correct dots. The test phase begins after participants reach a learning criterion of placing all the objects correctly in a single trial. During test, participants attempt to place the objects in the correct locations *without* the aid of the dots marking the locations and other structure organizing the locations (e.g., boundaries). It is important to note that participants are given no foreknowledge of the test prior to this point in the session. We record the x and y coordinates of each object to obtain a precise measure of where participants placed the objects. Our primary measures are mean and variable error (computed based on the absolute distance from the correct locations) and center displacement (the degree to which people place the objects belonging to the same spatial group closer together than they actually are). In this chapter, we focus primarily on the analyses of center displacement. We refer the reader to the published articles for a complete description of all results.

The focus of this work is on understanding how “decisions” about where to place the objects emerge out of the interaction of available task structure and the cognitive processes involved in coding, maintaining, and retrieving spatial information. We are especially interested in the tendency

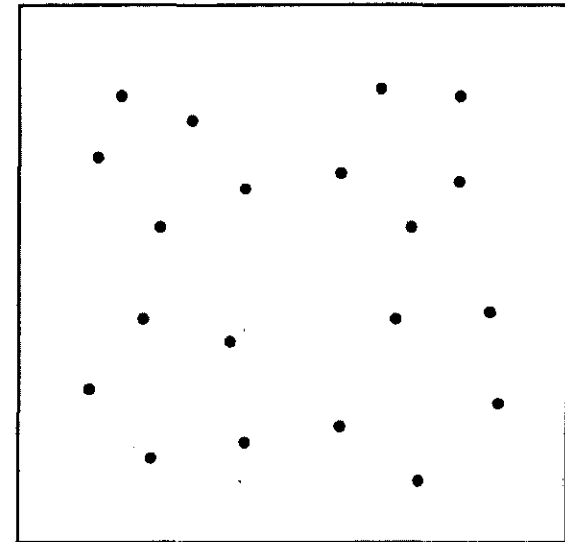


Figure 2.1 Layout of locations on the floor of the box.

to place objects belonging to the same spatial group closer together than they really are (i.e., categorical bias). Systematic bias in placements is thought to be a signature of the underlying processes that govern decisions about placements (Huttenlocher, Hedges, & Duncan, 1991; Spencer & Hund, 2002). As in the Category-Adjustment model proposed by Huttenlocher et al. (1991), we assume that children and adults code both fine-grained, metric information about the precise location of each object and coarse-grained, categorical information about the group or region to which each location belongs. Remembering the precise location of each object is necessary for distinguishing nearby locations from each other. Likewise, remembering the group to which each location belongs is useful for reducing the demands of remembering 20 individual locations. We assume that categorical bias reflects the “push” and “pull” of memory for both the individual locations and the spatial groups. When memory for the spatial groups (i.e., associations among locations in the spatial groups) is strong relative to memory for the individual locations, people place the objects closer together than they really are. Conversely, when memory for the individual locations is strong relative to memory for the spatial groups, people exhibit little or no categorical bias in their placements.

A major question underlying these notions about categorical bias is what governs the strength of memory for fine-grained and categorical information? From a traditional perspective, patterns of bias depend solely on how the cognitive system codes, maintains, and retrieves fine-grained and categorical information. At most, the environment plays a supporting role in providing cues for encoding and retrieving information. From an ecological perspective, however, environmental structure and the cognitive system are inextricably linked as part of a complete system. That is, patterns of bias emerge out of the *interaction* of structure available in the task and the characteristics of the cognitive system. Hence, both differences in the cognitive system and differences in the available perceptual structure can alter the interaction, leading to changes in the pattern of categorical bias. For example, we might expect to see more categorical bias when multiple cues are available to code the spatial groups during learning. Likewise, we might expect to see less categorical bias as people become more certain of the individual locations (e.g., through age-related changes in the precision of fine-grained coding). Experimental manipulations of either environmental structure (e.g., imposing boundaries that divide locations into groups) or the cognitive system (e.g., strengthening fine-grained memory through repeated opportunities for learning) can reveal the nature of these underlying interactions that govern object placements.

Across multiple experiments, our goal was to examine how bias in placements varies in response to manipulations of environmental structure while children and adults are coding and reproducing sets of locations. We have examined how categorical bias emerges out of interactions of task structure and coding processes by providing cues for organizing the locations into

groups during learning. In particular, we have examined how children and adults use visible boundaries subdividing the space, experience with visiting nearby locations close together in time, and categorical relatedness between objects occupying the same region to organize the locations into groups, leading to systematic variations in categorical bias at test (Hund & Plumert, 2003, 2005; Hund, Plumert, & Benney, 2002; Plumert & Hund, 2001). Likewise, we have examined how categorical bias varies in response to interactions of task structure and retrieval processes by varying the available perceptual structure at test (Plumert & Hund, 2001). Again, note that our focus is on using experimental manipulations of task structure to understand how interactions between the cognitive system and task structure produce systematic changes in decisions about where to place objects (i.e., categorical bias). This contrasts with a more traditional focus on using experimental manipulations of task structure to understand aspects of the cognitive system itself (e.g., using precues to understand how attention operates).

We have chosen to study 7-, 9-, and 11-year-old children and adults because we hypothesize that important developmental changes are occurring in the cognitive system during late childhood and early adulthood. These developmental changes fundamentally alter the interaction between the cognitive system and the task structure because they lead to differences in the amount and kind of information that is “available” for use. First, we hypothesize that the precision of fine-grained, metric coding is improving between the ages of 7 and 11 years (and possibly between 11 years and adulthood). In virtually every study that we have conducted to date, there is a linear decrease in mean and variable error across these ages (see also Hund & Spencer, 2003; Spencer & Hund, 2003). The hypothesized increase in the precision of fine-grained coding likely depends on recurrent organism–environment interactions that occur as children repeatedly face the problem of localizing objects, thereby leading to increasing sensitivity to distance and direction from landmarks (for related ideas, see Schutte & Spencer, 2002; Schutte, Spencer, & Schöner, 2003; Spencer & Hund, 2002, 2003). Second, we hypothesize that strategic coding of spatial information also may be increasing across this age range. When a cue for forming spatial groups (e.g., visible boundaries) is present during the learning phase, the group to which each object belongs is readily apparent. Adults may incorporate this information into an explicit spatial clustering strategy designed to reduce the demands of remembering all 20 object–location pairings (see also Plumert, 1994). Children notice the groups of locations but may be less likely to use this information strategically. As a result, adults form much stronger associations among the locations within each group than do children. These stronger associations increase the “pull” from the spatial groups, increasing the likelihood of bias in placements. In the next sections, we review specific evidence regarding the ways in which children and adults code and reproduce locations in the context of our location memory task.

2.2.1 Coding Locations: How Do Cues for Forming Spatial Groups Influence Categorical Bias?

We have carried out several studies examining how the availability of cues for forming spatial groups during learning affects categorical bias at test (Hund & Plumert, 2003, 2005; Hund et al., 2002; Plumert & Hund, 2001). We are especially interested in how the structure available for organizing the locations into groups (e.g., visible boundaries, spatiotemporal experience) interacts with characteristics of the cognitive system (i.e., age-related changes in the coding of fine-grained and categorical information) to produce particular patterns of categorical bias. Thus far, we have looked at three types of cues for forming spatial groups: visible boundaries subdividing the space, experience with visiting nearby locations close together in time, and categorical relations between objects occupying the same region. We have also examined how flexibly children and adults can shift between one organization of the locations and another as a function of the structure supporting each organization.

2.2.1.1 VISIBLE BOUNDARIES Visible boundaries that divide locations into groups are perhaps the most obvious source of perceptual structure for forming spatial groups (Allen, 1981; Kosslyn, Pick, & Fariello, 1974; McNamara, 1986; Newcombe & Liben, 1982). Our first study in this program of research examined how boundary salience during learning influenced categorical bias at test (Plumert & Hund, 2001). Seven-, 9-, and 11-year-old children and adults learned the locations of 20 unrelated objects in a random order. In the *walls* condition, interior walls the same height as the exterior walls divided the box into four quadrants. In the *lines* condition, lines on the floor divided the box into four quadrants. In the *no boundaries* condition, no visible boundaries were present. After participants reached the learning criterion, the test phase began. The experimenter removed the dots marking the locations and any boundaries subdividing the space. Participants then attempted to place the objects in the correct locations.

The primary question of interest was whether children and adults in each boundary condition placed the objects belonging to each group closer together than they actually were. As expected, participants exhibited greater categorical bias when boundaries were present during learning than when they were not present. In addition, they exhibited more categorical bias when more salient boundaries were present during learning than when less salient boundaries were present. One-sample *t*-tests comparing center displacement scores to the expected score of 0 revealed that both adults and 11-year-olds in the walls condition and adults in the lines condition placed the objects significantly closer together than they really were (see figure 2.2). In the no boundaries condition, however, children and adults showed very little categorical bias. In fact, 7-, 9-, and 11-year-olds placed the objects significantly farther from the category centers than they really were. Thus,

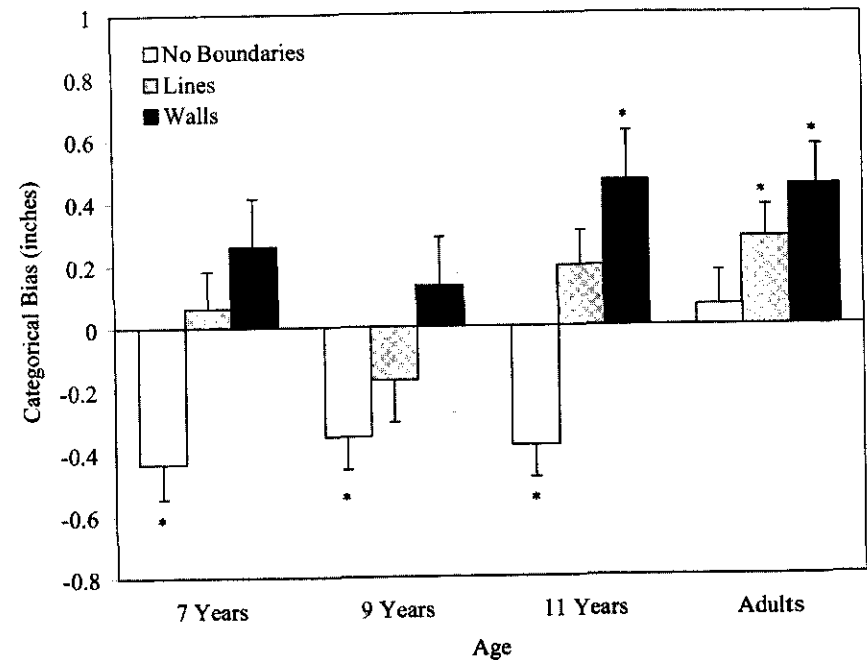


Figure 2.2 Categorical bias exhibited by each age group when boundaries were present or absent during learning. Positive scores reflect bias toward the category centers; negative scores reflect bias away from category centers. *Significant results ($p < .05$) of one-sample *t*-tests ($df = 11$) comparing the displacement score to the expected score with no displacement (i.e., 0 inches).

when no cues were available to organize the locations into groups, children and adults had difficulty forming strong associations among the locations within each quadrant of the box.

What do these results tell us about organism–environment interaction? As figure 2.2 shows, all age groups responded to boundary salience. Categorical bias was always highest in the walls condition, intermediate in the lines condition, and lowest in the no boundaries condition. This clearly shows that the salience of perceptual structure during learning affected categorical bias at test. More salient boundaries helped children and adults create stronger associations among the locations in the spatial groups as they were learning the locations. Stronger associations led to greater “pull” from the spatial groups when participants placed the objects at test. Note, however, that the magnitude of categorical bias in the three boundary conditions differed across the four age groups. This indicates that there were developmental differences in how the cognitive system interacted with the structure in the task. Unlike adults, children (with the exception of the 11-year-olds in the walls condition) did not place the objects in the spatial

groups significantly closer together than they really were. Subsequent studies have also revealed that children often do not show significant levels of categorical bias when only lines or walls divide the locations into groups (Hund & Plumert, 2002, 2003; Hund et al., 2002). Apparently, boundaries alone often are not sufficiently salient to help children form strong connections among the locations within the spatial groups. Without strong connections, children do not place objects closer together than they really are at test. These differences between children and adults underscore the idea that the extent to which children and adults make use of environmental structure is constrained by the characteristics of the organism. Even though children and adults were provided with the same perceptual structure during learning, adults were more able to make use of the organization than were children. Together, these findings highlight that understanding how the cognitive system and task structure interact is necessary to fully explain behavior.

2.2.1.2 EXPERIENCE WITH VISITING NEARBY LOCATIONS CLOSE TOGETHER IN TIME Another cue that people can use to form spatial groups is spatiotemporal experience (Clayton & Habibi, 1991; Curiel & Radvansky, 1998; McNamara, Halpin, & Hardy, 1992; Sherman & Lim, 1991). Specifically, experience with visiting several locations close together in time may lead people to form associations among those locations. For example, suppose a child and her parent spend Saturday morning shopping at several downtown stores and stop for lunch at a nearby restaurant. This spatiotemporally contiguous experience (and similar experiences on other days) may strengthen the relations among this particular restaurant and set of stores. As a result, the child and parent may think that this restaurant and set of stores are closer together than they really are. In many cases, temporal contiguity may be influenced by visible boundaries: physical barriers or perceptual boundaries may guide locomotion (or decisions about locomotion) such that people usually visit sites on one side of a boundary before visiting sites on the opposite side. These examples again illustrate the cyclical quality of organism–environment interactions over time. That is, structure in the environment constrains how people experience the environment. In turn, these experiences shape how the cognitive system organizes knowledge of the environment (see Mou & McNamara, 2002, for a discussion of “conceptual north”). Once in place, such knowledge constrains how people experience (i.e., interact with) the environment.

In the study described below, we examined how children and adults use spatiotemporal experience and visible boundaries to remember locations (Hund et al., 2002). Seven-, 9-, 11-year-old children and adults learned 20 locations with lines subdividing the box into four quadrants. In the *random learning* condition, participants learned the locations in a random order (i.e., our standard learning procedure). In the *contiguous learning* condition, participants experienced the locations belonging to each quadrant together in time during learning. Participants first watched while the experimenter placed all

five objects in one quadrant, then placed five objects in another quadrant, and so on. During the subsequent learning trials, the experimenter handed participants the objects from one quadrant before moving on to another quadrant. Thus, participants placed the objects quadrant by quadrant during the learning phase of the experiment. The order of quadrants and the order of locations within quadrants were randomized for each learning trial. For both conditions, the experimenter removed the dots marking the locations and the boundaries subdividing the box prior to test.

The primary question of interest was whether children and adults in each learning condition placed the objects belonging to each group closer together than they actually were. As shown in figure 2.3, adults placed objects belonging to the same spatial group significantly closer together than they really were in both the random and contiguous learning conditions. In contrast, none of the child age groups placed the objects significantly closer together than they actually were following random experience with the locations during learning. In the contiguous learning condition, however, 9- and 11-year-olds placed objects belonging to the same spatial group significantly closer together than they really were. Seven-year-olds showed a very similar pattern, but their center displacement scores in the contiguous learning condition did not differ significantly from 0 due to high variability in their placements.

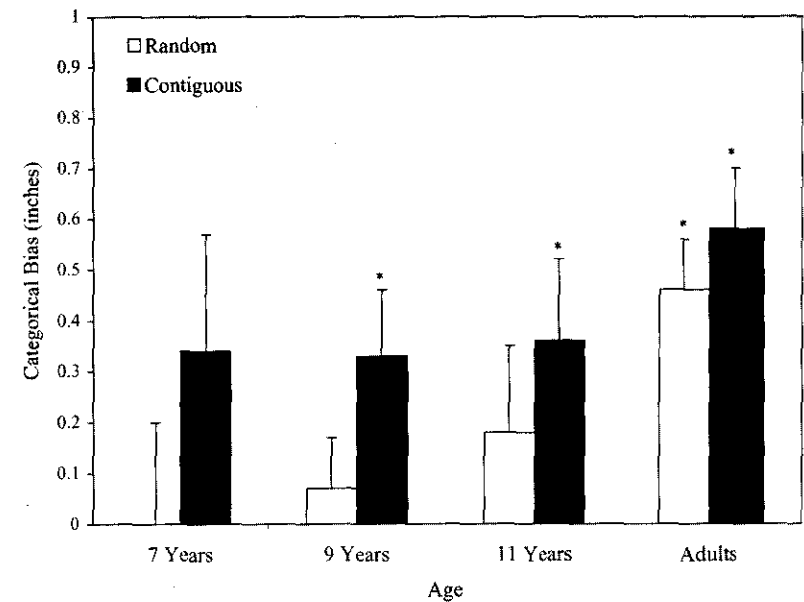


Figure 2.3 Categorical bias exhibited by each age group in the random and contiguous learning conditions. Positive scores reflect bias toward the category centers. *Significant results ($p < .05$) of one-sample t -tests ($df = 11$) comparing the displacement score to the expected score with no displacement (i.e., 0 inches).

The finding that adults exhibited categorical bias in both learning conditions whereas children only exhibited categorical bias in the contiguous learning condition again supports the idea that categorical bias emerges out of the interaction of task structure (e.g., spatiotemporal experience and visible boundaries) and the cognitive system. Adults easily formed strong associations among the locations within each group even when only a single cue (visible boundaries) organized the locations into groups. In contrast, children formed strong associations among the locations within each group only when two cues (visible boundaries and spatiotemporal contiguity) organized the locations into groups. Thus, age differences in the coding of fine-grained and categorical information interacted with the structure provided in the task to produce different patterns of categorical bias.

2.2.1.3 CATEGORICAL RELATIONS AMONG OBJECTS OCCUPYING NEARBY LOCATIONS Another type of environmental structure that people might use to form spatial groups is categorical relations among objects occupying nearby locations. In everyday environments, thematically or categorically related objects often are found together. For example, fruits, vegetables, dairy products, and meats are typically located in different areas of the grocery store. Quite likely, this kind of structure helps people organize locations into groups. In the experiments described below, we asked whether children and adults use categorical relations among objects to organize locations into groups (Hund & Plumert, 2003). Our goal was to examine how manipulations of environmental structure (i.e., categorical relations among objects occupying nearby locations) interact with age differences in the coding of fine-grained and categorical information to produce differences in patterns of categorical bias.

In Experiment 1, children and adults learned the locations of 20 objects belonging to four categories: animals, vehicles, food, and clothing. In the *related* condition, objects belonging to the same object category were located in the same quadrant of the box. In the *unrelated* condition, the same objects and locations were used, but they were randomly paired. In both conditions, the experimenter gave the objects to participants in a random order on each learning trial. After participants reached the learning criterion, they attempted to place the objects in the correct locations without the aid of the dots marking the locations. Of particular interest was whether participants in the related condition would place the objects belonging to the same group closer together than would participants in the unrelated condition, suggesting that children and adults use information about objects to organize memory for locations.

Overall, participants in the related condition placed the objects significantly closer to the centers of the spatial groups than did participants in the unrelated condition. As shown in figure 2.4, however, categorical bias in the related condition followed a U-shaped developmental pattern. Seven- and 9-year-olds and adults in the related condition placed the objects belonging to the same spatial group significantly closer together than they

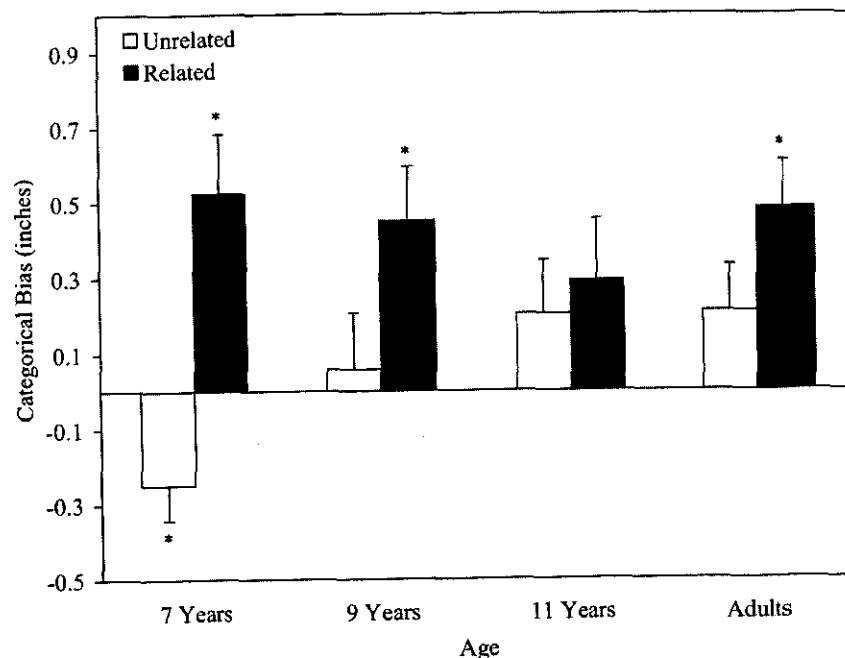


Figure 2.4 Categorical bias exhibited by each age group when categorically related or unrelated objects occupied the four quadrants of the box. Positive scores reflect bias toward the category centers; negative scores reflect bias away from category centers. *Significant results ($p < .05$) of one-sample t -tests ($df = 11$) comparing the displacement score to the expected score with no displacement (i.e., 0 inches).

actually were. In contrast, 11-year-olds in the related condition did not place the objects significantly closer together than they actually were. In the unrelated condition, both children and adults showed very little categorical bias. In fact, 7-year-olds placed the objects significantly *farther* from the category centers than they actually were and showed bias toward the corners of the box. Again, this shows that children and adults have trouble forming strong spatial groups in our task when no obvious cues are available to organize the locations into groups.

Why did the 11-year-olds in the related condition show only minimal categorical bias? One possibility is that their strong memory for the individual locations effectively counteracted the “pull” from their memory for the spatial groups. To test this possibility, we conducted a second experiment in which two categorical cues were present (i.e., object relatedness and visible boundaries), thereby increasing the strength of the spatial groups. All aspects of Experiment 2 were the same as in Experiment 1 except that visible boundaries divided the box into four quadrants during learning. We expected that 11-year-olds in the related condition would

place objects belonging to the same group closer together than would their counterparts in the unrelated condition, suggesting that coincident cues (i.e., visible boundaries and object relatedness) lead to stronger associations among the locations in the spatial groups.

As shown in figure 2.5, the pattern of categorical bias in the unrelated condition followed a U-shaped pattern. Thus, when unrelated groups of objects were separated by boundaries, the magnitude of categorical bias followed a U-shaped developmental pattern similar to that seen when related objects were not separated by visible boundaries. In contrast, the pattern of categorical bias in the related condition no longer followed a U-shaped pattern. Instead, all age groups placed the objects belonging to the same spatial groups significantly closer together than they really were. The finding that providing two coincident cues for coding the spatial groups (i.e., visible boundaries and object relatedness) erased the U-shaped pattern in categorical bias supports the claim that boosting the associations among the locations in the spatial groups changed the dynamics of the interaction. That is, strengthening the associations increased the “pull” of memory for spatial groups relative to memory for the individual locations, leading to increased categorical bias in 11-year-olds’ placements.

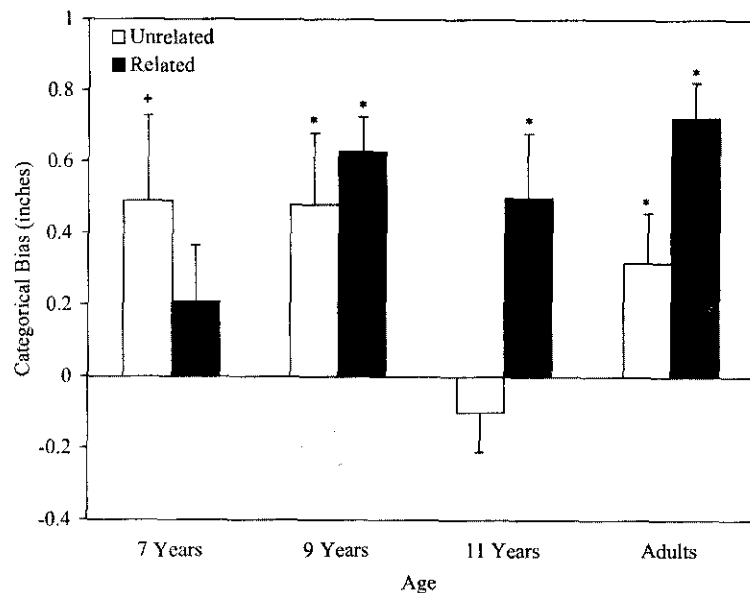


Figure 2.5 Categorical bias exhibited by each age group when categorically related or unrelated objects were divided by boundaries. Positive scores reflect bias toward the category centers; negative scores reflect bias away from category centers. *Significant results ($p < .05$) of one-sample t -tests ($df = 11$) comparing the displacement score to the expected score with no displacement (i.e., 0 inches).

The U-shaped developmental patterns of categorical bias seen in these experiments provide particularly compelling examples of organism–environment interaction because they illustrate how differences in the cognitive system and differences in the task structure alter the interaction between the cognitive system and the task structure, leading to changes in the pattern of categorical bias. On the side of the cognitive system, there are age-related changes both in the coding of fine-grained, metric information and in the coding of coarse-grained, categorical information. In all of our studies, adults exhibit significantly less mean and variable error than do the younger children. By 11 years of age, coding of fine-grained, metric information is nearly as good as that of adults. In contrast, strategic coding of the spatial groups appears to be undergoing change between 11 years of age and adulthood. Unlike children, adults form very strong associations among the locations in the spatial groups because they rely heavily on spatial clustering strategies to learn the locations. We hypothesize that adults exhibit strong categorical bias in their placements because their memory for the individual locations (though very good) cannot counteract the strong “pull” of the spatial groups. Eleven-year-olds often do not exhibit categorical bias in their placements because their strong memory for the individual locations effectively counteracts the weaker “pull” of the spatial groups. In contrast, 7- and 9-year-olds exhibit categorical bias in their placements because their relatively weak memory for the individual locations cannot counteract the “pull” from the spatial groups. Thus, the younger age groups exhibit categorical bias because their coding of the individual locations is relatively weak, whereas the adults exhibit categorical bias because their coding of the spatial groups is relatively strong. Together, these findings illustrate how characteristics of the cognitive system (e.g., age-related differences in the coding of fine-grained and categorical information) and structure available in the task (e.g., types of cues available for coding the spatial groups) jointly determine patterns of categorical bias.

2.2.1.4 STABILITY AND FLEXIBILITY IN ORGANIZING LOCATIONS INTO GROUPS Our interest in understanding how categorical bias emerges from organism–environment interactions has led us to examine the stability and flexibility with which children and adults organize locations into groups. By its very nature, flexibility implies an interaction between the characteristics of the cognitive system and structure available in the environment. For example, the ability to shift between two organizations of the same set of locations means that both the environmental structure specifying the different organizations and the cognitive processes necessary for picking up those organizations must be in place. Variations in either environmental structure or cognitive processes (or both) will alter the flexibility with which children and adults can shift between alternative organizations of the same set of locations.

We investigated how environmental structure and the cognitive system interact to produce flexibility in organizing locations in a series of four

experiments (Hund & Plumert, 2005). We will focus on the third and fourth experiments here. The basic design involved giving children and adults spatiotemporal experience specifying one organization of the locations at one point in time and then giving them spatiotemporal experience specifying another organization of the same locations at a later point in time. Of particular interest was how the perceptual structure in the task and the spatiotemporal experience with the locations interacted to produce different patterns of flexibility at different ages.

As in previous studies, the box contained 20 locations marked by dots. These locations were arranged so that they could be organized in two specific ways—each forming four groups of five locations. In one case, groups were located along each side of the box (i.e., the *side-defined* groups; see figure 2.6A), and in the other case, groups were located in each quadrant of the box (i.e., the *quadrant-defined* groups; see figure 2.6B). Displacement directions of eight target locations differentiated between the two patterns of organization. As shown in figure 2.6, the target locations were included in different groups depending on whether the side-defined or quadrant-defined groups were highlighted during learning. We used the eight target locations to calculate two displacement scores: a side displacement score and a quadrant displacement score. The side displacement score reflected the degree to which participants systematically placed the eight target objects closer to the corners corresponding to the side-defined groups than they actually were.

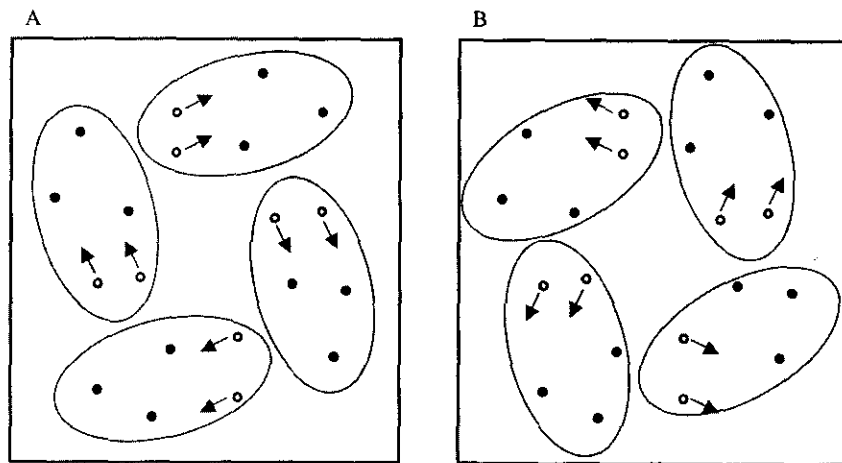


Figure 2.6 Diagram of the experimental apparatus and locations. Circles mark the 20 locations, and open circles mark the eight target locations. Ovals show the two different ways the 20 locations were experienced during learning in the side-defined and quadrant-defined conditions. Arrows show the predicted pattern of displacement for the target locations in each condition at test. (A) Locations experienced together in the side-defined condition. (B) Locations experienced together in the quadrant-defined condition. The arrows and ovals are for illustration only.

Conversely, the quadrant displacement score reflected the degree to which participants systematically placed the eight target objects closer to the corners corresponding to the quadrant-defined group than they actually were.

The experimental design included two testing sessions separated by approximately 5 days. During the first session, 7-, 9-, and 11-year-olds and adults experienced either the locations belonging to the quadrant-defined groups together in time during learning (Experiment 3) or the locations belonging to the side-defined groups together in time during learning (Experiment 4). After learning, participants attempted to replace the objects without the aid of the dots marking the locations. At the beginning of the second session, participants were asked to replace the original objects in the correct locations without the aid of the dots. This repeated assessment following a long delay provided an index of the stability of categories based on spatiotemporal cues. After this initial test, participants learned the locations of a new set of objects using a new spatiotemporal organization. The locations were identical to those learned at the first session; however, the objects and spatiotemporal organization differed across sessions. In Experiment 3, participants experienced locations belonging to the side-defined groups together in time, whereas in Experiment 4, participants experienced the locations belonging to the quadrant-defined groups together in time. In both experiments, comparison across sessions provided an index of flexibility in category formation.

This design allowed us to examine how spatiotemporal experience and perceptual structure interact to produce particular patterns of flexibility in spatial categorization. Note that in Experiment 3, the initial organization (during Session 1) was relatively strong because it was consistent with participants' spatiotemporal experience with the locations and with the perceptual structure of the task space (i.e., the axes of symmetry in the box). The subsequent organization (during Session 2) was not as strong because it was consistent with participants' spatiotemporal experience with the locations, but it was inconsistent with the perceptual structure of the task space. In contrast, in Experiment 4, the initial organization (during Session 1) was consistent with participants' spatiotemporal experience of the locations and inconsistent with the perceptual structure of the task space, whereas the subsequent organization (during Session 2) was consistent both with people's experience with the locations and with the perceptual structure of the task space.

Analysis of displacement scores revealed that adults demonstrated clear organization at Session 1, maintained this organization over a long delay, and flexibly shifted to a new organization at Session 2. For the children, the pattern of initial organization and stability was similar across the two experiments. All three age groups demonstrated clear organization during the test phase of Session 1 and remarkable stability of this organization over a long delay. In contrast, the pattern of flexibility differed across experiments. When children experienced the quadrant-defined groups together in time at Session 1 and the side-defined groups together in time at

Session 2, none of the age groups demonstrated a shift in organization following the change in spatiotemporal experience. When children experienced the side-defined groups together in time at Session 1 and the (stronger) quadrant-defined groups together in time at Session 2, 7- and 11-year-olds showed a clear shift in organization following the change in spatiotemporal experience.

These results again underscore the idea that the processes that give rise to categorical bias are dynamic, involving the interaction of the cognitive system (e.g., coding and maintenance of spatial information) and available perceptual structure over time. At Session 1, both children and adults organized the locations in ways consistent with the initial spatiotemporal organization they experienced. At Session 2, adults were able to shift to a new organization based on their subsequent experience with either the side-defined or the quadrant-defined groups of locations. In contrast, children (i.e., 7- and 11-year-olds) showed a shift in organization at Session 2 only when they experienced the quadrant-defined groups of locations together in time during the second session. That is, they demonstrated flexibility when the initial spatiotemporal organization conflicted with perceptual cues (e.g., when the side-defined groups were experienced together in time during the first session) and the new spatiotemporal organization was consistent with perceptual cues (e.g., when the quadrant-defined groups were experienced together in time during the second session). Children did not show a shift in organization when the initial spatiotemporal organization was consistent with perceptual cues and the new spatiotemporal organization conflicted with perceptual cues. Together, these results nicely illustrate how organism-environment interactions at one point in time (i.e., Session 1) affect organism-environment interactions at a later point in time (i.e., Session 2).

2.2.2 Reproducing Locations: How Does the Available Perceptual Structure at Test Influence Categorical Bias?

Thus far, we have discussed experimental manipulations designed to alter the interaction of the cognitive system and the task structure during learning. These findings leave open the question of how the cognitive system and the task structure interact when children and adults are in the process of replacing the objects during the test phase. We addressed this question by examining whether changing the available perceptual structure during the test phase influences categorical bias (Plumert & Hund, 2001). (Note that some of these data were presented above in our discussion of how the salience of boundaries during learning influences categorical bias.) In particular, do children and adults exhibit more categorical bias when boundaries are present during learning but not during test than when boundaries are present during both learning and test? We reasoned that taking away perceptual structure at test that was available at learning would be more disruptive to memory for fine-grained, metric information than to memory for coarse-grained, categorical information. Specifically, people likely rely

on boundaries and other landmarks to retrieve precise information about individual locations at test, whereas people may not need boundaries to retrieve memory for the spatial groups at test. Greater uncertainty about the individual locations (i.e., in the absence of boundaries) should lead to greater "pull" from the spatial groups. Hence, children and adults should exhibit more categorical bias when boundaries are absent than when present during test. Participants learned 20 locations with either walls or lines subdividing the box into four quadrants. During the test phase, boundaries were either present or absent while participants attempted to replace the objects without the aid of the dots.

As expected, participants exhibited more categorical bias, when no boundaries were present at test than when boundaries were present at test. One-sample *t*-tests comparing center displacement scores to 0 revealed that when boundaries were present during test, not even the adults showed significant categorical bias. In fact, 7- and 9-year-olds placed the objects significantly farther from the category centers than they really were (see figure 2.7). In contrast, when the boundaries were *not* present during test, 11-year-olds and adults in the walls condition and adults in the lines condition placed the objects closer together than they really were, exhibiting significant categorical bias.

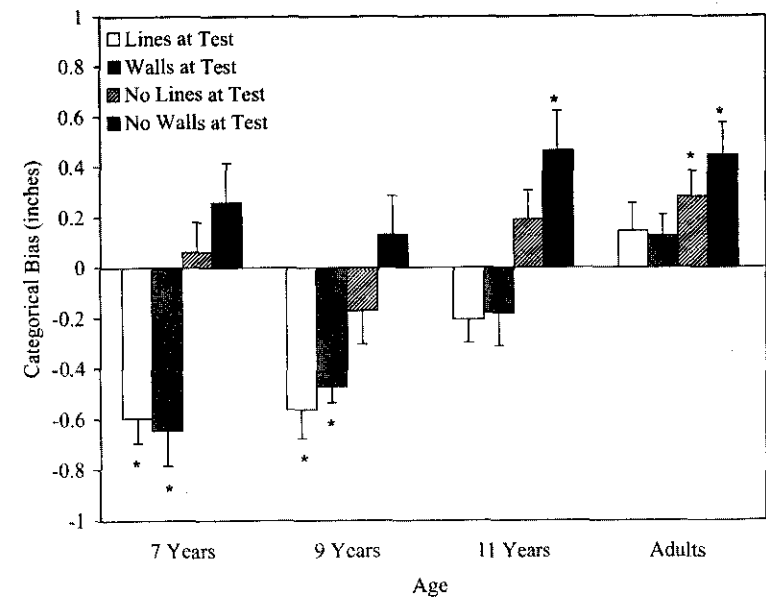


Figure 2.7 Categorical bias exhibited by each age group when there were boundaries or no boundaries during test. Positive scores reflect bias toward the category centers; negative scores reflect bias away from category centers. *Significant results ($p < .05$) of one-sample *t*-tests ($df = 11$) comparing the displacement score to the expected score with no displacement (i.e., 0 inches).

Given that all aspects of the procedure were the same up to the moment participants began placing the objects at test, these results demonstrate that decisions about where to place the objects during the test phase emerged out of the interaction of memory for the locations and perceptual structure available in the task at the time of test. In particular, we propose that during learning, adults coded the distance and direction of the locations relative to the boundaries and formed strong connections among the locations within each group. When the boundaries were present at test, adults could rely on their memory for the precise locations of the objects relative to the boundaries. When perceptual structure was absent at test, however, adults could not readily use their memory for the precise locations of the objects relative to the boundaries. (This idea is supported by better placement accuracy when boundaries were present than absent during test.) In the absence of boundaries during test, adults relied more heavily on their memory for the spatial groups, leading to greater categorical bias. Children also exhibited greater bias when boundaries were absent than when they were present at test, but with the exception of the 11-year-olds in the more salient boundary condition, the level of categorical bias was not significantly greater than 0. In fact, children exhibited significant pull toward the *corners* of the box, resulting in center displacement scores that were significantly less than 0. These findings suggest that children formed weaker connections among the locations within each group than did the adults. As a consequence, the “pull” from the spatial groups was not strong enough to offset their memory for the individual locations even when there was less perceptual support during test. Together, these results provide an intriguing example of how decisions about where to place the objects are not solely about what is in the head. Rather, placements emerge out of the interaction of the memory representation and the available perceptual structure.

2.3 CONCLUSIONS

The program of research presented here illustrates why we need the concept of organism–environment interaction to understand changes in spatial thinking over both short and long time scales. The experiments showing that U-shaped developmental patterns of categorical bias can be created or destroyed depending on the presence of single versus multiple cues for forming spatial groups (Hund & Plumert, 2003) provide particularly compelling examples of organism–environment interaction because they illustrate how categorical bias depends both on the characteristics of the cognitive system (e.g., age-related changes in coding and maintaining fine-grained and categorical information) and on the structure available in the task (e.g., single vs. multiple cues). In short, differences in the cognitive system and differences in the task structure alter the interaction between the cognitive system and the task structure, leading to systematic changes in the pattern of categorical bias.

From this way of thinking, neither the cognitive system nor environmental structure has causal priority in explaining behavior. We cannot explain patterns of categorical bias by referring only to task structure (e.g., presence or absence of boundaries) or by referring only to developmental differences in the cognitive system (e.g., strategic encoding of spatial groups). Our studies have repeatedly shown that all age groups exhibit categorical bias under some task conditions but not under others. For example, adults always show significant categorical bias when at least one cue is available during learning, but they do not show bias when no cues are available during learning. Thus, it is impossible to predict categorical bias by referring to age alone. Likewise, our studies have repeatedly shown that the four age groups frequently differ in how they respond to the same task structure. For example, children and adults often differ in how they respond to cues for organizing the locations into groups, such as visible boundaries, spatiotemporal experience, or object relations. Clearly, children and adults extract different things from their experience with these tasks even though the task structure is identical for all participants. These variations in how the same age group responds to different task structure and how different age groups respond to the same task structure support the idea that categorical bias emerges out of the interaction of the cognitive system and the task structure.

2.3.1 Understanding Change Over Short Time Scales

A key question raised by our results is *how* do interactions between the cognitive system and the task structure give rise to particular patterns of categorical bias? First, interactions that occur when people are coding locations determine the strength of memory for the individual locations and the spatial groups. (Note that the strength of these representations can change if delays are imposed between learning and reproducing locations; see Hund & Plumert [2002].) As discussed throughout this chapter, we assume that strong coding of the individual locations preserves precise metric information about distance and direction, whereas strong coding of the spatial groups (i.e., associations between the locations belonging to the same spatial group) pulls locations toward each other in memory. Task structure that highlights the spatial groups (e.g., multiple cues for forming spatial groups) should lead to stronger associations between locations belonging to the same spatial group. Likewise, task structure that makes it easier to code the individual locations (e.g., repeated opportunities to learn the locations) should lead to stronger memory for the individual locations (see Recker, Plumert, & Hund, 2006).

Second, we propose that these memory representations interact with the perceptual structure available at test to produce “decisions” about where to place the objects. How might this work? We assume that when children and adults are replacing the objects, they are trying to recreate an array that “matches” the remembered array (i.e., an array that “looks right” to them).

Their ability to recreate the remembered array depends both on the similarity of perceptual structure between learning and test and on the state of their memory for the individual locations. When perceptual structure at test is dissimilar to that available during learning (e.g., boundaries are present at learning but not at test) or when memory for the precise locations becomes fuzzy (e.g., due to delays between learning and test or restricted opportunities to learn the locations), people have difficulty creating a visual array that matches the remembered array (see Hund & Plumert, 2002; Recker et al., 2006). In sum, when there is a weak coupling between what people remember and what they see, placements can become ungrounded. This then opens the door for systematic bias such as compression of distances between objects in the same spatial group (or drift away from a midline axis; see Spencer & Hund, 2003).

2.3.2 Understanding Change Over Developmental Time Scales

Thus far, we have focused on how organism–environment interactions lead to changes in thinking that emerge in the moment or over brief time scales (i.e., the course of the experiment). But how do organism–environment interactions lead to changes in thinking over the longer term? Of particular interest is how changes come about in the fine-grained coding of individual locations and the coarse-grained coding of spatial groups. We start with the assumption that long-term developmental change emerges out of recurrent organism–environment interactions (see also Newcombe & Huttenlocher, 2000). That is, changes in the cognitive system lead to increased sensitivity to environmental structure for coding location. In turn, increased sensitivity to environmental structure leads to change in the cognitive system (e.g., more precise coding of individual locations or more strategic coding of spatial groups). From this perspective, interaction with environmental structure for coding location is necessary to produce changes in the organism, but the amount and type of structure that are “available” (i.e., can be used) at any point in development are constrained by the characteristics of the cognitive system. In the paragraphs that follow, we focus on ideas about how the ability to form spatial groups might emerge. (For ideas about how changes in the coding of fine-grained detail might come about, see chapter 14.)

We propose that developmental change in the ability to organize locations into groups emerges out of experience with noticing salient cues that highlight connections among nearby locations and with using spatial clustering strategies in supportive tasks. Although research directly comparing cues for forming spatial groups is scarce, a handful of studies have shown that the salience of cues influences how easily children organize locations into groups (Hund & Plumert, 2005; Kosslyn et al., 1974, Newcombe & Liben, 1982; Nichols-Whitehead & Plumert, 2001; Plumert & Hund, 2001). For example, Nichols-Whitehead and Plumert (2001) found that 3- and 4-year-olds’ object retrieval was more organized when a tall opaque

or short opaque boundary divided a small dollhouse in half than when a tall transparent boundary divided the dollhouse in half. Thus, it appears that children respond to more visually salient boundaries before they respond to less visually salient boundaries. More recently, we found that 7- to 11-year-old children used spatiotemporal contiguity to form spatial groups when they experienced *all* of the locations in one group together before moving on to the next group, but not when they experienced only 75% of the locations in one group together before moving on to another group (Hund & Plumert, 2005). In contrast, adults used spatiotemporal contiguity to form spatial groups in both conditions. Again, this suggests that sensitivity to structure for forming spatial groups undergoes change during development. Over the long term, we assume that children’s experiences with more salient structure heighten their sensitivity to less salient structure for forming spatial groups. At this point, however, we know of no empirical demonstrations that this is the case (even within the course of an experiment). Clearly, this is an issue that requires further investigation, perhaps within the context of a microgenetic study.

Experience with using spatial clustering in highly supportive tasks may also produce developmental change in children’s sensitivity to spatial groups. Spatial clustering refers to the tendency to order locations based on proximity or membership in a spatial region or group, such as visiting nearby locations together in time when searching for a hidden object. A number of studies have shown that older children use spatial clustering in a broader range of tasks than do younger children (e.g., Cornell & Heth, 1986; Plumert, 1994; Plumert, Pick, Marks, Kintsch, & Wegesin, 1994; Wellman, Somerville, Revelle, Haake, & Sophian, 1984). For instance, one of the first ways in which children use spatial clustering is in searching for objects. Thus, 4-year-olds retrieve the objects from one cluster of locations before retrieving those in another cluster (Wellman et al., 1984). Somewhat later, children begin to use their spatial clustering skills in verbal tasks such as giving directions for finding missing objects (Plumert et al., 1994). By 12 years of age, children also use spatial clustering to structure their free recall of object locations. Thus, when asked to recall the locations of a set of objects, 12-year-olds recall the locations by spatial region (Plumert, 1994, Experiment 2). Finally, at around 16 years of age, adolescents apply spatial clustering to structure their recall of object names. When recalling the furniture from their home, for example, 16-year-olds, but not younger children, group furniture items by room (Plumert, 1994, Experiment 1).

We hypothesize that children first use strategies in tasks that make the relevant features of the problem more salient (Folds, Footo, Guttertag, & Ornstein, 1990; Gauvain, 1993; Miller, 1990). To use a spatial clustering strategy, children must focus on the spatial connections among the locations. Tasks such as searching for objects, giving directions for finding objects, and recalling the names of objects differ in how explicitly they draw attention to the spatial connections among the object locations. For example, a task such as giving directions to someone for finding a set of objects

may readily draw younger children's attention to the spatial connections among objects by making the listener's movement through space more salient. Specifically, imagining the listener in the space may prime them to think about locations nearby the listener (Morrow, Greenspan, & Bower, 1987). When faced with an unstructured task such as free recall, however, younger children may have difficulty focusing on the spatial connections among the objects because the explicitly stated goal of the task is to remember what the objects are, not where they are located. In fact, in situations in which both categorical and spatial organization are available (e.g., recalling the furniture from one's home), younger children attend more to the categorical than to the spatial relations among the items (Plumert, 1994).

Children's experiences with repeatedly using spatial clustering in highly supportive task contexts may guide their attention to the spatial connections among objects. Once cued about these spatial connections, children may be able to use their spatial clustering skills in less supportive task contexts, leading to the emergence of spatial clustering in tasks that provide less spatial support. In fact, there is evidence showing that experience with using spatial clustering in a more supportive task facilitates children's ability to use spatial clustering in a less supportive task. Plumert et al. (1994) found that when 6-year-olds gave directions for finding a set of objects and then went to search for those objects, they exhibited low levels of spatial clustering in their directions but high levels of spatial clustering in their searches. However, when they were allowed to search for the objects before giving directions for finding them, they exhibited high levels of spatial clustering in their subsequent directions. These results suggest that although children apply their spatial clustering skills to searching before they apply those same skills to giving directions, experience with using spatial clustering during searching facilitates 6-year-olds' ability to apply their spatial clustering skills to the more difficult task of direction giving.

Likewise, Plumert and Strahan (1997) found that 10-year-olds could be induced to use spatial clustering in a free recall task if given experience with using spatial clustering in a tour-planning task first. In contrast, 8-year-olds exhibited relatively low levels of spatial clustering in their subsequent free recall regardless of whether they performed the tour-planning task or the free recall task first. These results suggest that experience with the more supportive tour-planning task cued 10-year-olds about the spatial connections among the objects. Once cued, 10-year-olds could apply a spatial clustering strategy to the less supportive free recall task. Thus far, these empirical demonstrations of transfer are limited to situations in which the child transfers a spatial clustering strategy from a simpler to a more complex task, but with the same objects and locations. Further work is needed to determine whether children can transfer spatial clustering strategies from simpler to more complex tasks when the objects and locations change as well.

Do noticing salient cues for forming spatial groups and using spatial clustering strategies in supportive tasks act as mechanisms for change in everyday life? In the laboratory, we can carefully control the order in which

children experience cues or tasks. Children's everyday experiences with cues for forming spatial groups and tasks calling for spatial clustering strategies are likely to be considerably less orderly. For example, children may be exposed to less salient cues for forming spatial groups before they are exposed to highly salient cues. Likewise, they may encounter more difficult tasks before they encounter less difficult ones. However, the sensitivity of the cognitive system to environmental structure may provide a built-in mechanism for ensuring that children's everyday experiences are more orderly than they may seem at first glance. With an immature cognitive system, young children's "experiences" may well be limited to noticing only salient cues for forming spatial groups and using spatial clustering in highly supportive tasks. Thus, young children do not experience a bewildering array of inputs simply because they are not sensitive to these inputs. This constraint on experience imposed by the cognitive system may be critical for ensuring that the child's experience of environmental structure proceeds in an orderly fashion. (See Newport [1990] for similar ideas about how immature cognitive abilities might constrain young children's experiences with linguistic input.)

2.3.3 CONCLUDING THOUGHTS Although the idea of the complementarity between the organism and environment may not seem like a particularly radical (or even novel) idea, much of the work in cognitive development implicitly rejects the idea that thinking is a joint function of the characteristics of the organism and the structure of the environment (for similar assessments, see Elman et al., 1996; Thelen & Smith, 1994). For example, some researchers interested in uncovering innate concepts or core knowledge have argued for a separation of cognitive competence and task performance (Baillargeon, 2001; Spelke, 2000). This has led to a never-ending search for the "right" task to tap some underlying core competence. Likewise, researchers interested in showing how learning experiences or task conditions influence thinking are often most interested in studying the cognitive system per se rather than in understanding how thinking emerges out the interaction of the task and the cognitive system (Cohen, 2004; Rovee-Collier, 1999). Although describing the information available in the environment and describing the characteristics of the cognitive system are necessary and important endeavors, they are only beginning steps to understanding how cognition happens in the moment and changes over time. We argue that researchers must ultimately focus on the interactions of the cognitive system and environmental structure over time to fully understand how thinking emerges over short and long time scales.

ACKNOWLEDGMENTS This work was supported by grants from the National Institutes of Health (R03-HD36761) and the National Science Foundation (BCS-0343034) awarded to J.M.P. and from the National Institutes of Health (F31-MH12985) awarded to A.M.H. We gratefully acknowledge the many undergraduate research assistants who helped with data collection and coding. We also thank the children and parents who participated in these studies.

REFERENCES

- Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development*, 62, 1-164.
- Adolph, K. E. (2000). Specificity of learning: Why infants fall over a veritable cliff. *Psychological Science*, 11, 290-295.
- Adolph, K. E., Eppler, M. A., & Gibson, E. J. (1993). Crawling versus walking infants' perception of affordances for locomotion over sloping surfaces. *Child Development*, 64, 1158-1174.
- Allen, G. L. (1981). A developmental perspective on the effects of "subdividing" macrospatial experience. *Journal of Experimental Psychology: Human Learning and Memory*, 7, 120-132.
- Baillargeon, R. (2001). Infants' physical knowledge: Of acquired expectations and core principles. In E. Dupoux (Ed.), *Language, brain, and cognitive development: Essays in honor of Jacques Mehler* (pp. 341-361). Cambridge, MA: MIT Press.
- Clayton, K., & Habibi, A. (1991). Contribution of temporal contiguity to the spatial priming effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 17, 263-271.
- Cohen, L. B. (2004). Modeling the development of infant categorization. *Infancy*, 5, 127-130.
- Cornell, E. H., & Heth, C. D. (1986). The spatial organization of hiding and recovering of objects by children. *Child Development*, 57, 603-615.
- Curiel, J. M., & Radvansky, G. A. (1998). Mental organization of maps. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24, 202-214.
- Elman, J. L., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: MIT Press.
- Eppler, M. A., Adolph, K. E., & Weiner, T. (1996). The developmental relationship between infant's exploration and action on slanted surfaces. *Infant Behavior & Development*, 19(2), 259-264.
- Folds, T. H., Footo, M. M., Guttentag, R. E., & Ornstein, P. A. (1990). When children mean to remember: Issues of context specificity, strategy effectiveness, and intentionality in the development of memory. In D. F. Bjorklund (Ed.), *Children's strategies: Contemporary views of cognitive development*. Hillsdale, NJ: Lawrence Erlbaum.
- Gauvain, M. (1993). The development of spatial thinking in everyday activity. *Developmental Review*, 13, 92-121.
- Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, 39, 1-41.
- Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development*. New York: Oxford University Press.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Hillsdale, NJ: Lawrence Erlbaum.
- Gibson, J. J., & Gibson, E. J. (1955). Perceptual learning: Differentiation or enrichment? *Psychological Review*, 62, 32-41.
- Hund, A. M., & Plumert, J. M. (2002). Delay-induced bias in children's memory for location. *Child Development*, 73, 829-840.
- Hund, A. M., & Plumert, J. M. (2003). Does information about what things are influence children's memory for where things are? *Developmental Psychology*, 39, 939-938.
- Hund, A. M., & Plumert, J. M. (2005). The stability and flexibility of spatial categories. *Cognitive Psychology*, 50, 1-44.
- Hund, A. M., Plumert, J. M., & Benney, C. J. (2002). Experiencing nearby locations together in time: The role of spatiotemporal contiguity in children's memory for location. *Journal of Experimental Child Psychology*, 82, 200-225.
- Hund, A. M., & Spencer, J. P. (2003). Developmental changes in the relative weighting of geometric and experience-dependent location cues. *Journal of Cognition & Development*, 4, 3-38.
- Huttenlocher, J., Hedges, L. V., & Duncan, S. (1991). Categories and particulars: Prototype effects in estimating spatial location. *Psychological Review*, 98, 352-376.
- Kosslyn, S. M., Pick, H. L., Jr., & Fariello, G. R. (1974). Cognitive maps in children and men. *Child Development*, 45, 707-716.
- Lockman, J. J. (2000). A perception-action perspective on tool use development. *Child Development*, 71, 137-144.
- McNamara, T. P. (1986). Mental representation of spatial relations. *Cognitive Psychology*, 18, 87-121.
- McNamara, T. P., Halpin, J. A., & Hardy, J. K. (1992). The representation and integration in memory of spatial and nonspatial information. *Memory & Cognition*, 20, 519-532.
- Miller, P. H. (1990). The development of strategies of selective attention. In D. F. Bjorklund (Ed.), *Children's strategies: Contemporary views of cognitive development*. Hillsdale, NJ: Lawrence Erlbaum.
- Morrow, D. G., Greenspan, S. L., & Bower, G. H. (1987). Accessibility and situation models in narrative comprehension. *Journal of Memory and Language*, 26, 165-187.
- Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, 162-170.
- Newcombe, N. S., & Huttenlocher, J. (2000). *Making space: The development of spatial representation and reasoning*. Cambridge, MA: MIT Press.
- Newcombe, N., & Liben, L. S. (1982). Barrier effects in the cognitive maps of children and adults. *Journal of Experimental Child Psychology*, 34, 46-58.
- Newport, E. L. (1990). maturational constraints on language learning. *Cognitive Science*, 14, 11-28.
- Nichols-Whitehead, P., & Plumert, J. M. (2001). The influence of boundaries on young children's searching and gathering. *Journal of Cognition and Development*, 2, 367-388.
- Plumert, J. M. (1994). Flexibility in children's use of spatial and categorical organizational strategies in recall. *Developmental Psychology*, 30, 738-747.
- Plumert, J. M., & Hund, A. M. (2001). The development of memory for object location: What role do spatial prototypes play? *Child Development*, 72(2), 370-384.
- Plumert, J. M., Kearney, J. K., & Cremer, J. F. (2004). Children's perception of gap affordances: Bicycling across traffic-filled intersections in an immersive virtual environment. *Child Development*, 75, 1243-1253.
- Plumert, J. M., Pick, H. L., Jr., Marks, R. A., Kintsch, A. S., & Wegesin, D. (1994). Locating objects and communicating about locations: Organizational differences in children's searching and direction-giving. *Developmental Psychology*, 30, 443-453.

- Plumert, J. M., & Strahan, D. (1997). Relations between task structure and developmental changes in children's use of spatial clustering strategies. *British Journal of Developmental Psychology*, *15*, 495–514.
- Recker, K. M., Plumert, J. M., & Hund, A. M. (2006). *How do biases in memory for location change over learning?* Unpublished Manuscript.
- Rieser, J. J., Pick, H. L., Ashmead, D. H., & Garing, A. E. (1995). Calibration of human locomotion and models of perceptual-motor organization. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 480–497.
- Rovee-Collier, C. (1999). The development of infant memory. *Current Directions in Psychological Science*, *8*, 80–85.
- Schutte, A. R., & Spencer, J. P. (2002). Generalizing the dynamic field theory of the A-not-B error beyond infancy: Three-year-olds' delay- and experience-dependent location memory biases. *Child Development*, *73*, 377–404.
- Schutte, A. R., Spencer, J. P., & Schöner, G. (2003). Testing the dynamic field theory: Working memory for locations becomes more spatially precise over development. *Child Development*, *74*, 1393–1417.
- Sherman, R. C., & Lim, K. M. (1991). Determinants of spatial priming in environmental memory. *Memory & Cognition*, *19*(3), 283–292.
- Spelke, E. S. (2000). Core knowledge. *American Psychologist*, *55*, 1233–1243.
- 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., & Hund, A. M. (2003). Developmental continuity in the processes that underlie spatial recall. *Cognitive Psychology*, *47*, 432–480.
- Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.
- Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 683–703.
- Wellman, H. M., Somerville, S. C., Revelle, G. L., Haake, R. J., & Sophian, C. (1984). The development of comprehensive search skills. *Child Development*, *55*, 472–481.

3

EXPLAINING THE DEVELOPMENT OF SPATIAL REORIENTATION

Modularity-Plus-Language versus the Emergence of Adaptive Combination

NORA S. NEWCOMBE & KRISTIN R. RATLIFF

All mobile organisms occasionally face the important adaptive problem of determining where they are when they have been disoriented by rapid movement (e.g., tumbling down a hill) or by passive movement without visual landmarks (e.g., traveling by subway). It has recently been proposed that a wide array of nonhuman animal species, as well as human children, solve this problem using a geometric module that only accepts information about the shape of enclosing spaces (Cheng, 1986; Gallistel, 1990; Hermer & Spelke, 1994, 1996; see Cheng & Newcombe, 2005, for an overview). In a modular view, various sources of spatial information are processed independently in separable cognitive processing units (e.g., Wang & Spelke, 2002). However, investigators have argued that, starting at 6 years of age in humans, productive control of spatial language, specifically the terms “right” and “left,” allows the operation of this geometric module to be supplemented by the use of featural information, such as the color of surfaces in the environment (e.g., Hermer-Vazquez, Moffett, & Munkholm, 2001; Hermer-Vazquez, Spelke, & Katsnelson, 1999).

Modularity is typically associated with nativist views (although this relation is by no means forced by logic; Fodor, 2001). However, there is a problem for innatist modularity claims: how to explain developmental change. In the case of the geometric module, Spelke and associates have