

# CHILDREN'S THINKING IS NOT JUST ABOUT WHAT IS IN THE HEAD: UNDERSTANDING THE ORGANISM AND ENVIRONMENT AS A UNIFIED SYSTEM

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## I. Introduction

Traditional approaches to cognition view thinking as something that sits exclusively within a person's head. An implicit assumption of this view is that thinking can occur independent of the physical, social, or task environment. Yet this view is at odds with the plethora of data showing wide variations in thinking across different environmental contexts, from controlled laboratory experiments to naturalistic observation studies (e.g., Correa-Chavez, Rogoff, & Arauz, 2005; Oakes, Plumert, Lansink, & Merryman, 1996; Plumert & Strahan, 1997; Samuelson, Schutte, & Horst, 2007). Even what appear to be small variations in task instructions (e.g., Plumert & Strahan) or minor differences in response measures (e.g., Huttenlocher *et al.*, 2008) can lead to rather large differences in performance.

One response to this dilemma is to conclude that certain performance demands or experimental contexts “mask” children’s true abilities (Baillargeon, 2001; Sophian, 1997; Spelke, 2000; Spelke & Newport, 1998). The problem with this view is that there is a never-ending search for the “right” task to tap underlying cognitive competencies (i.e., the one that results in the best performance at the youngest age). Another response to the problem is to characterize children’s abilities as emerging in pieces or steps over development, with rudimentary aspects of skills emerging in simpler task contexts at earlier points in development (e.g., Huttenlocher *et al.*, 2008; Woolley, 2006). This approach takes seriously the problem of identifying the task components that lead to different response patterns in different test situations. At its core, however, this approach shares the assumption that the environment sits outside of the thinking process.

The goal of this chapter is to attempt (once again) to move the field away from the separation of the organism and the environment by focusing on the idea of emergence. The central idea is that thinking is not just about what is in the child’s head. Rather, thinking emerges out of the interaction of the cognitive system and environmental structure (i.e., the physical, social, or task environment). From this perspective, the environment is not just an “influence” on thinking or development. Rather, the child and the environment are part of a unified system. In this chapter, I illustrate these ideas by reviewing two lines of research on the development of spatial categorization skills. These two programs of research focus on children’s use of spatial categories to organize their recall and to remember object positions. The goals of the chapter are twofold. One is to describe how age changes in children’s spatial categorization skills depend both on the child and the environment. The other, more difficult goal is to speculate about how these changes come about.

## II. The General Theoretical Framework

The notion that thinking emerges from the interaction of the organism and the environment has been central to several major theories over the last century, including those of Piaget (1954), Vygotsky (1978), Thelen and Smith (1994), Gottlieb (Gottlieb & Lickliter, 2007), and the Gibsons (J. J. Gibson, 1979; E. J. Gibson, 1988). In this chapter, I focus primarily on ideas about organism–environment interaction from J. J. and E. J. Gibson. A critical concept introduced by the Gibsons is the complementarity of the organism and environment. In other words, possibilities for action (i.e., affordances) 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; Gibson & Pick, 2000; Lockman, 2000; Plumert, Kearney, & Cremer, 2004, 2007b; Rieser *et al.*, 1995; Warren, 1984). Thus, changes in the environment and changes in the organism (or both) lead to changes in possibilities for action. For example, 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. We can see this experimentally by engineering either the organism (e.g., adding heavy or light weights to the child’s backpack) or the environment (e.g., changing the steepness or slipperiness of the slope). In this chapter, I expand this view of perception to the domain of cognition. In other words, perceiving, acting, and *thinking* emerge out of the interaction of the characteristics of the organism and the characteristics of the environment. Moreover, I argue that this view of organism–environment interaction provides a particularly good framework for conceptualizing how spatial thinking emerges over time.

What does it mean to say that 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 other words, 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 up to the field of information processing) and the structure available in the environment (the physical, social, and task environment) for guiding thinking.

What are the implications of this view for understanding changes in spatial thinking over longer 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; 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; Gibson & Gibson, 1955). I 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 with 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, increased use of spatial clustering strategies might sensitize children to 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.

Note that this framework for understanding developmental change in children's spatial thinking has much in common with Vygotsky's notions about scaffolding and the zone of proximal development. The basic premise underlying this approach to cognitive development is that children often acquire knowledge and skills through social interaction with more skilled individuals. Adult guidance of cognitive performance is thought to be particularly important during times of transition, sometimes referred to as the zone of proximal development (Vygotsky, 1978). During such times, children are sensitive to experiences that allow them to try out new ways of thinking and acting. More specifically, children are in a state of readiness to benefit from guidance that provides them with the necessary support to use their skills in novel ways. Over time, scaffolding can be modified or withdrawn as the child becomes increasingly competent at executing the skill. Developmental change results as responsibility for structuring cognitive performance shifts from the adult to the child.

Subsequent reformulations of Vygotsky's (1978) contextual approach to cognitive development stress the notion of "guided participation" as a vehicle for cognitive change (Gauvain, 2001; Rogoff, 1990). Guided participation emphasizes both active participation of children and guidance from others as contributors to the process of change. According to Rogoff (1990), older, more experienced individuals such as parents capitalize on children's eagerness to learn by providing guidance that will advance children's skills and understanding. From this perspective, the primary task for the adult is to provide guidance that is appropriately geared to the developmental level of the child. That is, adults must provide guidance that supports, and yet challenges children's skills and understanding.

The concept of scaffolding has been almost exclusively applied to the role of social interaction in promoting cognitive change. However, these notions about scaffolding can be expanded to encompass to the physical context and the task context. In other words, highly supportive structure in the physical or task environment provides young children with the scaffolding necessary to execute particular skills. Repeated experience with supportive physical or task environments allows young children to refine their skills.

Over time, children begin to use these same skills in less supportive physical and task environments. Again, it is important to point out that scaffolding from the social, physical, or task environment alone does not produce developmental change. Environmental structure cannot influence the child's thinking unless the child has the necessary background knowledge or processing capabilities to notice this structure. Likewise, the child cannot develop new background knowledge or refine her processing capabilities without exposure to environmental structure. Importantly, this perspective on developmental change shifts the focus from only considering the changes that occur within the child or the environmental factors that impact performance to considering how organism-environment interactions change over development.

I now turn to considering empirical examples of organism-environment interaction drawn from our work on the development of spatial cognition. 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. Note that I draw both on concepts about the characteristics of the cognitive system from mainstream information-processing approaches and on ideas about the structure of the environment from a traditional ecological approach. Although the two approaches are rarely considered together, ideas from both lead to a much richer picture of spatial thinking and development than does either one alone.

### III. The Development of Spatial Categorization

The ability to organize locations within some kind of spatial structure is fundamental to the process of learning and remembering locations. Without this structure, remembering the locations of the countless objects and places encountered everyday would become insurmountable. By organizing knowledge of location, memory demands are lessened because locations are not treated as isolated pieces of spatial information. In this section, I review two lines of research on the development of spatial categorization. The first concerns how children come to use spatial categorization as an organizational device to enhance recall of objects and locations. The second line of research concerns the role that spatial categorization plays in remembering object positions. Both lines of research serve as illustrations of how thinking emerges out of the interaction of the cognitive system and environmental structure.

#### A. USING SPATIAL CATEGORIES TO ORGANIZE RECALL

In general, spatial clustering refers to grouping objects or locations on the basis of common membership within a spatial region. Typically, spatial regions are defined by physical or perceptual boundaries, or by proximity to salient landmarks (Huttenlocher & Lourenco, 2007; McNamara, 1986). For example, one might think of a table, stool, and refrigerator as belonging together because they are all located in the kitchen, or one might think of a couch, rug, and rocking chair as belonging together because they are all located near the fireplace. We might also think of a region as a cluster of nearby objects or places such as pieces of play equipment on a schoolyard or a group of university buildings on campus. In the real world, cues for forming spatial groups typically overlap. For example, a spatial group might be defined by perceptual boundaries, salient landmarks, and close proximity of objects. These cues can function as the basis for spatial organizational strategies for retrieving or recalling sets of objects. When recalling objects from home, for example, one might retrieve or recall objects in the kitchen, then the objects in the living room, then the objects in the laundry room, and so on.

##### 1. The Development of Spatial Organizational Strategies

A large body of research indicates that spatial clustering strategies do not develop in an all-or-none fashion. Rather, more sophisticated use of spatial clustering strategies emerges gradually over childhood, starting during the preschool years. A major part of this development is using spatial clustering strategies in increasingly complex tasks. One of the first manifestations of spatial clustering is young children's tendency to retrieve the items in one spatial region before retrieving items in another spatial region (Cornell & Heth, 1986; Haake, Somerville, & Wellman, 1980; Plumert *et al.*, 1994; Wellman *et al.*, 1984). For example, Wellman *et al.* (1984) found that 4- and 5-year-olds minimized the number of traverses they made between two clusters of locations while retrieving Easter eggs they had previously seen hidden in five buckets on a playground. Similarly, Cornell and Heth (1986) found that both 5- and 7-year-olds hid objects in spatial clusters and tended to search those clusters exhaustively when later retrieving the objects. These results suggest that the ability to use spatial organization to guide physical activity emerges fairly early in development.

Given young children's use of spatial clustering to guide the organization of their own movements, to what extent do they use spatial clustering to guide the organization of another person's movements? We examined this question by comparing the order in which 6-year-olds and adults searched

for objects with the order in which they referred to object locations in their route directions (Plumert *et al.*, 1994). The basic paradigm involved having children and adults help an experimenter hide nine small tokens along an inefficient random route on the three levels of their home. After all the tokens were hidden, participants were asked to go find them all again or to tell another experimenter how to go find all those pieces through a walkie-talkie. Comparison of the routes children produced in their searches and verbal directions showed that they used an efficient order to retrieve the objects themselves (i.e., organized their searches by floor), but directed the other person to the locations in an order that resulted in a very inefficient search. Adults, in contrast, both searched efficiently and gave efficient directions. Interestingly, although children did not spontaneously order the locations by floor in their directions, they demonstrated that they had the necessary spatial knowledge to do so because they were able to give spatially efficient directions if prompted after each direction to tell the listener where the next closest object was. This suggests that young children were able to use visual cues and the actual physical structure of the layout to help them organize their searches, but were unable to mentally access that structure to produce spatially organized directions unless their listener provided an explicit organizational framework. In sum, 6-year-old children exhibited a marked difference in their use of spatial clustering to organize their searches and directions, even when all other aspects of the situation were equated.

These results naturally raise the question of when do children begin to use spatial clustering in their verbal directions? We investigated this question in a study comparing the organization of children's free recall and tour plans (Plumert & Strahan, 1997). Note that although tour planning and direction giving are not the same tasks, both require the person to think about the order in which another person will visit or search a set of locations. In this study, 6-, 8-, and 10-year-old children first helped an experimenter hide 16 unrelated objects in a 4-room dollhouse (see Figure 1). After hiding the objects the first time, children were asked to turn around so

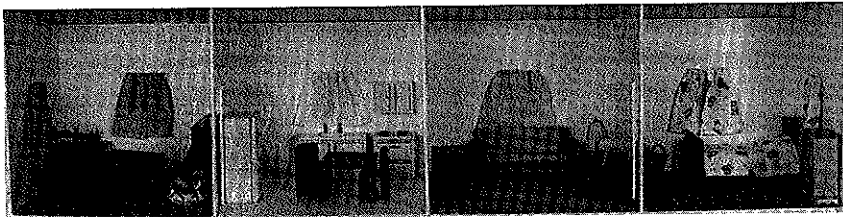


Fig. 1. The four-room dollhouse used as the experimental space.

that they faced away from the dollhouse. The experimenter then removed the objects from the dollhouse. After children turned to face the dollhouse again, the experimenter handed them the objects in a different random order and asked them to put the objects back exactly where they were before. The experimenter immediately corrected any placement mistakes. This procedure was repeated until children reached the criterion of correctly replacing all 16 objects in a single trial. After children completed the location learning procedure, the experimenter placed an opaque cover over the entire dollhouse. Children in the free recall condition then were instructed to name as many of the hidden objects as they could remember. Children in the tour-planning condition were then asked to plan a tour of the hidden objects for a doll figure. The experimenter instructed children to "tell me which one you would show him first, and second, and so on." Thus, all aspects of the experiment were the same except for the task used to get children to name the objects.

We calculated Adjusted Ratio of Clustering (ARC) scores to assess the degree of spatial clustering (i.e., ordering the objects by room) in children's tour plans and free recall (Roemer, Thompson, & Brown, 1971). As shown in Figure 2, 6-year-olds showed equally low levels of spatial clustering in both their tour plans and free recall. The difference between 8-year-olds' ARC scores in the tour plan and free recall conditions approached conventional levels of significance. Thus, 8-year-olds in the tour-planning condition showed somewhat higher levels of spatial clustering than did their counterparts in the free recall condition. Finally, 10-year-olds in the tour-planning condition had significantly higher spatial clustering scores than did 10-year-olds in the free recall condition. The results of this investigation clearly show that the task context plays a major role in children's use of spatial clustering. Specifically, children's use of spatial clustering in the tour-planning task increased gradually between the ages of 6 and 10. At none of the ages tested, however, did children spontaneously use spatial clustering in the standard free recall task. Again, it is important to point out that all aspects of the experiment were the same up to the point children were given the task instructions, indicating that spatial clustering emerged out of the interaction of the child and the task.

When do children use spatial clustering to organize their free recall of object names? I addressed this question by asking 10-, 12-, 14-, 16-year-olds, and adults to recall the furniture from their home (Plumert, 1994). Making a furniture inventory from memory is a particularly interesting task for investigating organizational strategies because furniture items can be grouped either by spatial region (e.g., kitchen, living room, bedroom, laundry) or by object category (e.g., tables, chairs, beds, dressers). Furthermore, because adults and children have repeated experience with their

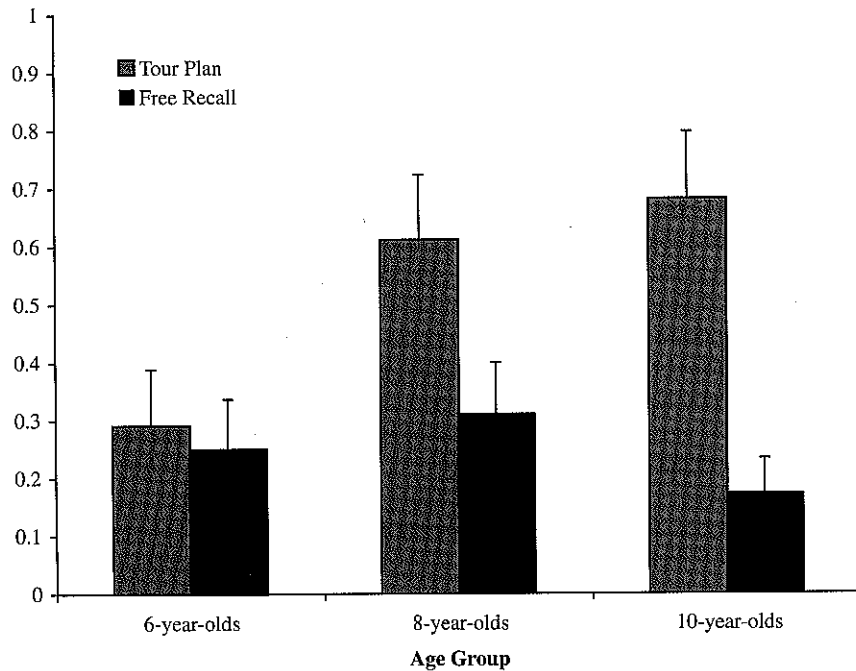


Fig. 2. Mean spatial clustering scores in the tour-planning and free recall conditions by age.

furniture, both the locations and types of furniture in their home are very well known to them. Quite surprisingly, analysis of spatial and categorical ARC scores revealed that 10-year-olds significantly preferred to organize their furniture by category than by room (see Figure 3). In contrast, the 16-year-olds and adults showed a strong preference for spatial over categorical organization. The 12- and 14-year-olds showed about equal use of both organizations. This pattern of results clearly shows that children's use of spatial clustering strategies to organize their recall of object names changes between 10 and 16 years of age. Specifically, 10-year-olds seem to have difficulty using their spatial clustering strategies to structure their recall of object names. Twelve- and 14-year-olds may be moving into a more transitional age in which there are large individual differences in spatial and categorical organization. This idea is supported by the fact that there were strong correlations between spatial organization and number of furniture items recalled for these ages. By 16 years of age, adolescents are clearly able to use what according to adult standards appears to be the most appropriate strategy for the task of recalling furniture from their home.

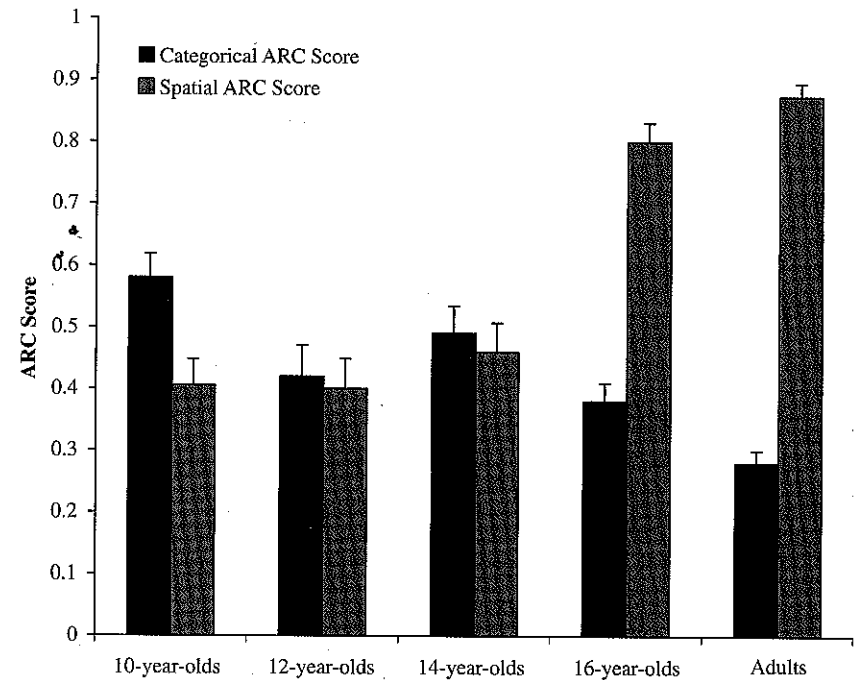


Fig. 3. Mean spatial and categorical clustering scores in the furniture inventory task by age.

This unanticipated developmental change in preferences for categorical and spatial organization raised the question of whether these preferences could be pushed around by manipulating the nature of the task. In a second experiment, 10- and 12-year-olds learned the locations of 16 toy objects that were divided into four object categories (vehicles, animals, clothing, and furniture). The objects were hidden in four rooms, with one of each type of object in each room. After hiding all the objects, children were taken to each location again in the same order as they hid the objects to give them a second chance to learn the object-location pairings. After seeing the objects the second time, children were taken to a separate testing room and given two recall tasks. The first task was to recall the toys they had hidden. The second task was to recall each object and where it was hidden. As expected, both 10- and 12-year-olds exhibited more categorical than spatial clustering when recalling just the objects. However, the 12-year-olds exhibited more spatial than categorical clustering when recalling the objects and their locations. Thus, 12-year-olds were more sensitive to the changing nature of the recall task than were 10-year-olds. Again, these results underscore the

point that thinking emerges out of the interaction of the child's information-processing skills and the structure of the task.

## 2. Summary

The work described here clearly shows that children's use of spatial organizational strategies differs by age and task. At the youngest ages, children use spatial clustering strategies to organize their searches for objects, but not their directions for finding objects or tour plans for viewing objects. At intermediate ages, children use spatial clustering to organize their directions and tour plans, but they do not use spatial clustering to organize their free recall of objects. At the oldest ages, children use spatial clustering in all tasks, including free recall. Together, these studies clearly illustrate that spatial clustering strategies do not reside in the head. Rather, they are an emergent property of a system that includes both the cognitive system and the environment.

## B. USING SPATIAL CATEGORIES TO REMEMBER OBJECT POSITIONS

The work described in the previous section clearly shows that spatial categories play an important role in organizing recall of objects and locations. As with other memory strategies, spatial clustering serves an important function of enhancing the number of items one can recall. But does forming a spatial category (e.g., grouping furniture items by room or floor) also play a role in remembering object positions? In particular, do people think that locations from the same spatial category are closer together than they really are?

### 1. Making Judgments about Locations

One of the first hints that spatial categories play a role in memory for location came from adult priming studies in which people read the names of two objects presented one after the other and then tried to make a judgment about the second object as quickly as possible. For example, people might be asked to judge whether or not the second object was present in the collection of objects in a layout they had previously learned. The rationale behind this approach is that if locations from the same spatial region are closely associated in memory, then the time required to respond to an object should be faster if it is preceded by the name of an object from the same region than from a different region. Indeed, a number of these spatial priming studies have shown that adults are faster to respond to an object if

it is preceded by the name of an object from the same region than a different region (e.g., McNamara, 1986; McNamara, Hardy, & Hirtle, 1989). This occurs even when the object from the different region is physically closer to the target object than is the one from the same region as the target object. These findings suggest that people remember objects from the same region (i.e., spatial category) as closer together than they really are.

The errors adults make when judging spatial relations also underscore the importance of spatial categories in memory for location. For example, Seattle is usually judged to be farther south of Montreal, when in fact it is farther north (Friedman & Brown, 2000a; Montello, 2003; Stevens & Coupe, 1978). Presumably, this error occurs because individuals rely on the north-south relations between the larger geographic regions to judge spatial relations between locations contained within those regions. Similar studies with children have also shown that spatial categories exert a powerful influence on their memory for locations (e.g., Acredolo & Boulter, 1984; Allen, 1981; Kosslyn, Pick, & Fariello, 1974; Newcombe & Liben, 1982). When asked to make spatial judgments about individual locations belonging to different spatial regions, for example, even 6-year-olds tend to rely on the overall spatial relations between regions rather than on the actual spatial relations between the individual locations (Acredolo & Boulter, 1984). Similarly, Allen (1981) found that 7- and 10-year-olds and adults tend to partition routes into subdivisions, and use these subdivisions to make distance judgments about locations along the route. In particular, children and adults often judged locations from two adjoining subdivisions as more distant than locations within the same subdivision even when the locations within the same subdivision were more physically distant than the locations from adjoining subdivisions. Together, these studies show that spatial categories play an important role in judgments about spatial relations.

### 2. Reproducing Previously Seen Locations

Subsequent work focused on whether children and adults show similar kinds of biases when physically reproducing previously seen locations (e.g., Engebretson & Huttenlocher, 1996; Huttenlocher, Hedges, & Duncan, 1991; Huttenlocher, Newcombe, & Sandberg, 1994; Sandberg, Huttenlocher, & Newcombe, 1996). Most of these studies involve briefly showing children and adults single locations in a homogenous space and then asking them to reproduce those locations in the same space. For example, in the sandbox task developed by Huttenlocher, Newcombe, and colleagues, children between the ages of two and 10 years watched an experimenter hide a toy in a long, narrow sandbox (Huttenlocher *et al.*, 1994). After a short delay in which children were turned away from the sandbox, they were allowed to

search for the toy. Analysis of search patterns indicated that all age groups exhibited systematic biases toward the region centers. Specifically, 2- and 6-year-olds' searches were biased toward the center of the entire sandbox, and 10-year-olds' searches were biased toward the centers of the two halves of the sandbox. Older children and adults show similar biases in tasks where they are asked to reproduce the location of a dot inside a circle or a line inside a 90° angle. In particular, older children and adults place locations closer to the centers of the circle quadrants and to the halves of the 90° angle than they actually are (Engebretson & Huttenlocher, 1996; Sandberg *et al.*, 1996). Together, these studies have repeatedly shown that children and adults alike show systematic biases toward the centers of geometric regions, supporting the idea that spatial categories play an important role in memory for location.

### 3. Categorical Bias as an Emergent Product of the Organism-Environment System

Our work on spatial category effects in memory for location focuses on understanding how "decisions" about where to place objects emerge out of the interaction of available environmental structure and the cognitive processes involved in coding, maintaining, and retrieving spatial information. 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 in. high) placed on the floor of a laboratory room (see Figure 4). We typically

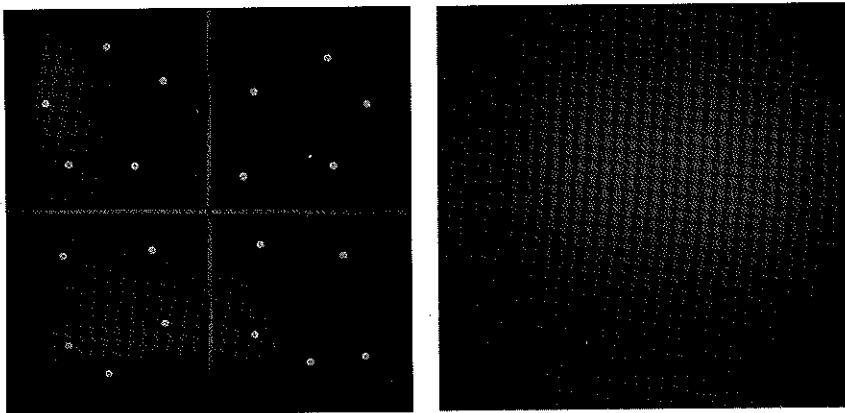


Fig. 4. Box used as the experimental space. The left panel shows the floor of the box with boundaries during learning. The right panel shows the floor of the box at test.

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 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).

*a. Where Does Bias Come From?* Systematic bias in memory for location is seen as an important signature of the underlying processes involved in reproducing previously seen locations (Huttenlocher *et al.*, 1991; Plumert, Hund, & Recker, 2007a; Spencer *et al.*, 2007). A key question is where does this bias come from? According to the category-adjustment model proposed by Huttenlocher *et al.* (1991), retrieval of locations from memory is a hierarchical process involving the use of both fine-grained and categorical information. When trying to remember a previously learned location, people make estimates based on their memory of fine-grained, metric information such as distance and direction from an edge. However, because memory for fine-grained information is inexact, people adjust these estimates based on categorical information about the location represented by a prototype located at the center of the spatial region or group. Hence, adjustments based on categorical information lead to systematic distortions toward the centers of spatial categories. According to this model, the magnitude of distortion toward category centers depends on the certainty of the fine-grained, metric information. When memory for fine-grained information is relatively certain, categorical information receives a low weight, resulting in only small distortions toward category centers. Conversely, when memory for fine-grained information is relatively uncertain, categorical information receives a high weight, resulting in large distortions toward category centers. The end result of such systematic bias is that responses are less variable, leading to greater overall accuracy.



Subsequently, Spencer, Schöner, and colleagues developed the dynamic field theory of spatial memory to account for spatial biases that often occur when people attempt to reproduce single locations after short delays (Johnson, Spencer, & Schöner, in press; Simmering, Schutte, & Spencer, in press; Spencer *et al.*, 2007). The dynamic field theory is a neural network model that captures how location-related activation in a network of neurons can be sustained from moment-to-moment and drift over short time periods. Briefly, the model consists of several interconnected layers (i.e., fields). These layers include perceptual, working memory, and long-term memory fields, as well as inhibitory interneurons. The perceptual field forms peaks of activation generated by input from perception of visible reference frames and the current target's (visible) location. The perceptual field passes activation about both the reference frame (e.g., an axis) and the target location to the working memory field. The working memory field passes self-sustained activation on to an associated long-term memory field. This field accumulates traces of activation representing the locations of other previously seen targets, with stronger traces associated with more frequently seen targets. The long-term memory field also passes activation back to the working memory field. Drift over time (i.e., bias) can occur through the interaction of the working memory and long-term memory fields, producing bias toward frequently remembered targets (Spencer & Hund, 2002, 2003). According to the dynamic field model, spatial biases emerge in a primarily bottom-up fashion out of moment-by-moment interactions among multiple components of the system.

The fact that we ask participants to remember the locations of 20 objects at one time makes our task considerably more complex than the tasks used to test the category adjustment and dynamic field theory models. As in both of these models, we assume that children and adults code fine-grained, metric information about the precise location of each object. Remembering the precise location of each object is necessary for distinguishing nearby locations from each other and for reproducing locations in an accurate manner. We also assume that children and adults code coarse-grained, categorical information about the group or region to which each location belongs. Clearly, remembering the group to which each location belongs is useful for reducing the demands of remembering 20 individual locations. Quite likely, coding spatial groups in our task involves the contribution of top-down, strategic processes that results in forming strong associations among the members of the spatial groups. We assume that categorical bias in placements reflects the "pull" of memory for the spatial groups. Specifically, 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 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. Paralleling perception-action research (e.g., Adolph, 1997; Plumert *et al.*, 2004), 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 has been 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; Recker, Plumert, & Stevens, 2007a). Again, 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-, 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, younger children exhibit greater mean and variable error than do older children and adults (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 information about distance and direction (for related ideas, see Schutte & Spencer, 2002; Schutte, Spencer, & Schöner, 2003; Spencer & Hund, 2002, 2003). Second, the use of spatial clustering strategies is also increasing across this age range. As discussed previously, adults readily use spatial clustering strategies to help them recall both objects and locations (Plumert, 1994). Children's use of spatial clustering undergoes significant change across childhood, not reaching adultlike performance until early to mid adolescence. As a result, adults may form much stronger associations among the locations within a spatial group than do children. These stronger associations increase the "pull" from the spatial groups, thereby increasing the likelihood of bias in placements. In the next sections, I illustrate how categorical bias in placements emerges out of the interaction of the organism and the environment in the context of our location memory task.

*b. 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.

**I. VISIBLE BOUNDARIES.** Visible boundaries that divide locations into groups are perhaps the most obvious source of perceptual structure for forming spatial groups. As discussed previously, numerous studies have shown that both children and adults tend to underestimate distances between locations within the same region and overestimate distances between locations in different regions (Allen, 1981; Kosslyn *et al.*, 1974; McNamara, 1986; Newcombe & Liben, 1982). In our initial work on categorical bias in estimates of location, we examined how boundary salience during learning influenced categorical bias at test (Plumert & Hund, 2001). Seven-, 9-, 11-year-olds 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.

To what extent did children and adults in each boundary condition place 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. 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 5). In the no boundaries condition, however, children and adults showed very little categorical bias. Thus, when no cues were available to organize the locations into groups, even adults had difficulty forming strong associations among the locations within each spatial group.

What do these results tell us about how the cognitive system and environmental structure interact to produce patterns of categorical bias? As Figure 5 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. We hypothesize that more salient boundaries helped children and adults create stronger associations among the locations in the spatial

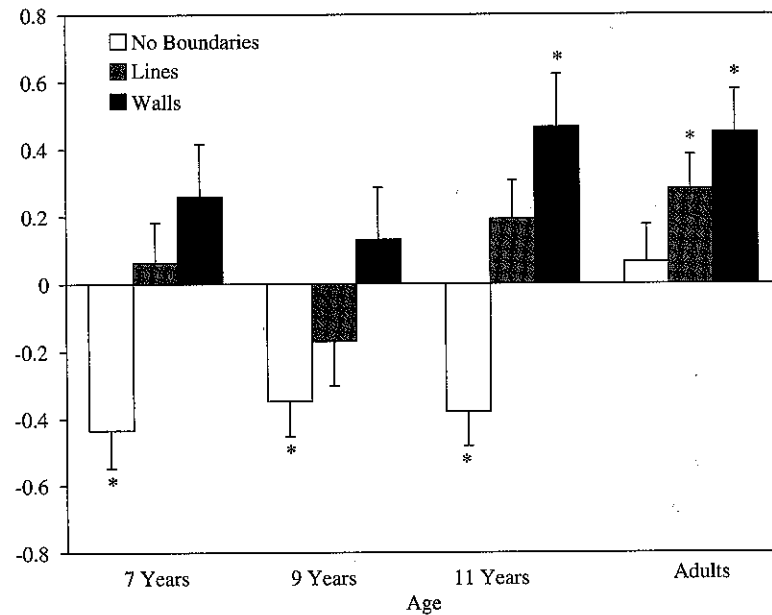


Fig. 5. Mean categorical bias in lines, walls, and no boundaries conditions by age. Asterisks denote significant results ( $p < .05$ ) of one-sample  $t$ -tests comparing the displacement score to the expected score with no displacement. Positive scores reflect bias toward the category centers.

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 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 environmental structure operate as a complete system is necessary to fully explain behavior.

II. 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 children and adults to form associations among those locations. For example, suppose a child has a paper route that involves delivering papers to the same set of houses on one side of town. This spatiotemporally contiguous experience may strengthen the relations among this particular set of houses. Not surprisingly, the child may come to think that these houses are much closer together than they really are. In many cases, such experiences with temporal contiguity are influenced by visible boundaries. In particular, physical barriers or perceptual boundaries guide locomotion (or decisions about locomotion) so that people usually visit sites on one side of a boundary before visiting sites on the opposite side. For example, the set of houses along the paper route may also be bordered by salient boundaries such as railroad tracks or major streets.

We examined how children and adults use spatiotemporal experience and visible boundaries to remember locations by manipulating the order in which children and adults learned the locations in our spatial memory task (Hund *et al.*, 2002). Seven-, 9-, 11-year-olds 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 6, 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, following random experience with the locations during learning, at no age did children place objects significantly closer together than they actually were. 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.

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

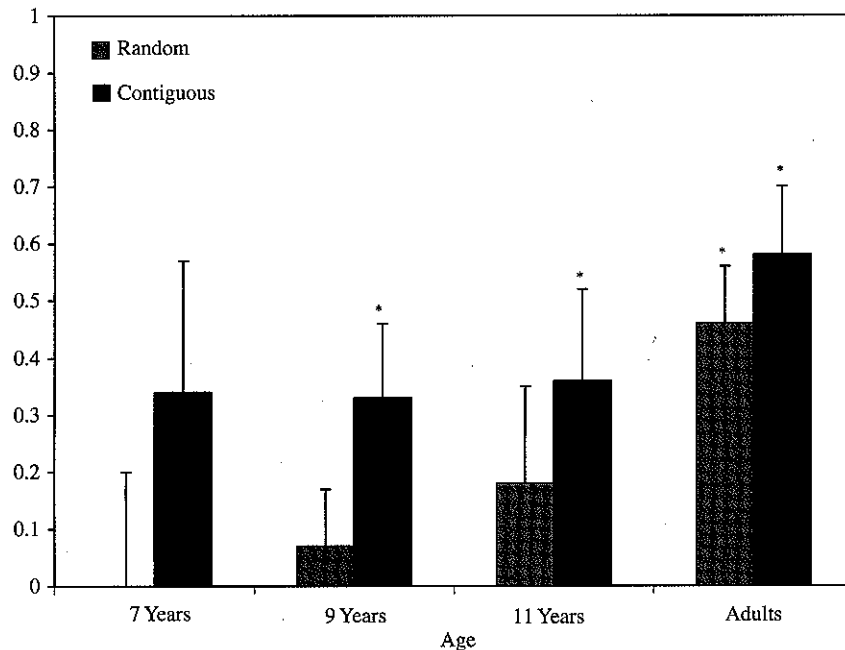


Fig. 6. Mean categorical bias in random and contiguous conditions by age. Asterisks denote significant results ( $p < .05$ ) of one-sample  $t$ -tests comparing the displacement score to the expected score with no displacement. Positive scores reflect bias toward the category centers.

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 only formed strong associations among the locations within each group 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.

III. CATEGORICAL RELATIONS AMONG OBJECTS OCCUPYING NEARBY LOCATIONS. Another type of cue 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, shoes, housewares, clothing, and cosmetics are typically located in different areas of a department store. Quite likely, this kind of structure helps people organize locations into groups. Such groupings are useful both for organizing retrieval (e.g., one is likely to retrieve items from one section before moving on to another section) and for cueing recall (e.g., one might try to recall needed items by thinking about which items are in each section).

We examined whether categorical relations among nearby objects play a role in memory for location by manipulating whether the objects in each quadrant of the box were from the same object category (Hund & Plumert, 2003). 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 7, however, categorical bias in the related condition followed a U-shaped developmental pattern.

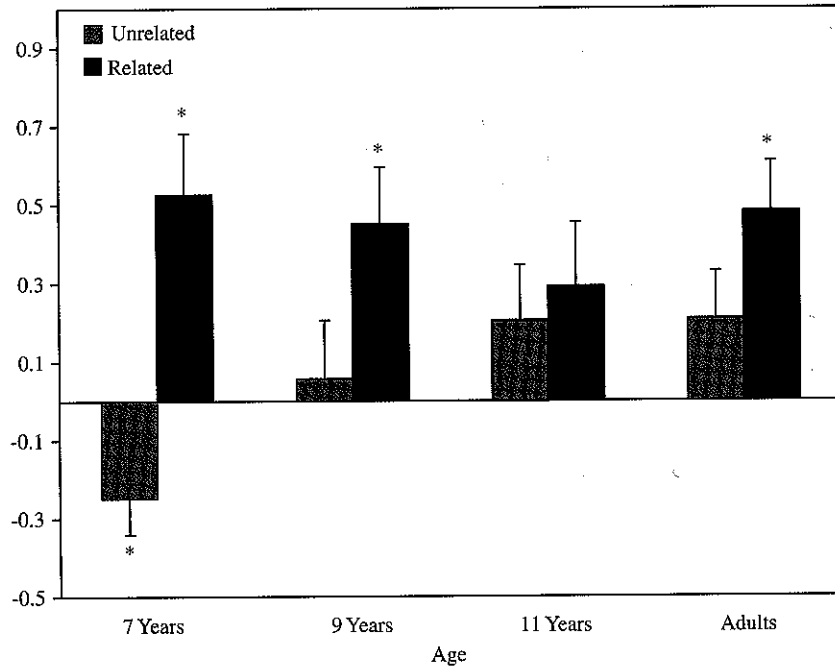


Fig. 7. Mean categorical bias by age in related and unrelated conditions when no boundaries were present during learning. Asterisks denote significant results ( $p < .05$ ) of one-sample  $t$ -tests comparing the displacement score to the expected score with no displacement. Positive scores reflect bias toward the category centers.

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 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 *further* from the category centers than they actually were (they 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 visible 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 8, 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

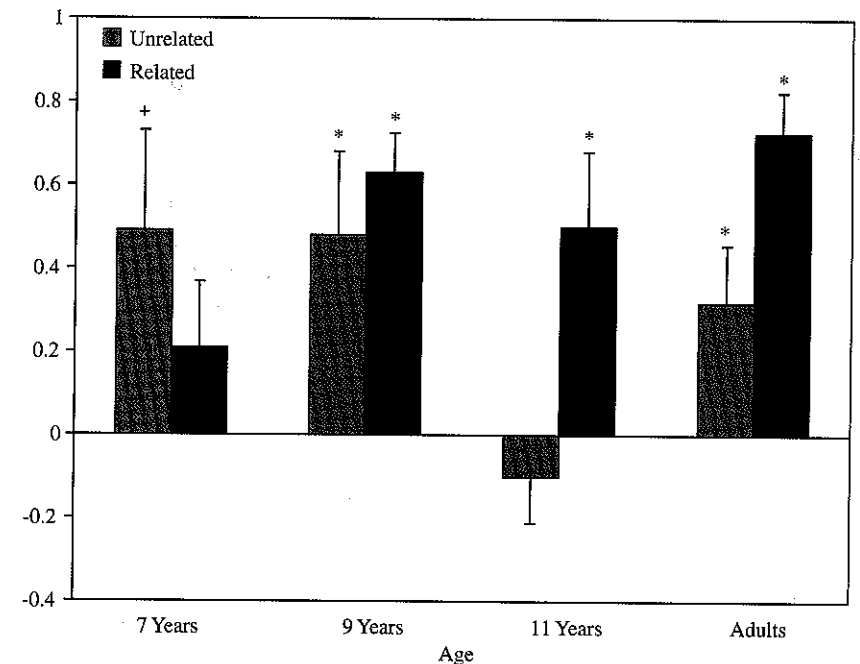


Fig. 8. Mean categorical bias by age in related and unrelated conditions when boundaries were present during learning. Asterisks denote significant results ( $p < .05$ ) of one-sample  $t$ -tests comparing the displacement score to the expected score with no displacement. Positive scores reflect bias toward the category centers.

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.

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 environmental structure alter the interaction between the cognitive system and the environmental 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.

*c. Reproducing Locations: How Does the Available Perceptual Structure at Test Influence Categorical Bias?* Thus far, I 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 earlier in the chapter in the 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 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. How was the tendency to place objects closer together than they really were influenced by the presence or absence of boundaries at test? As expected, participants exhibited more categorical bias when no boundaries were present at test than when boundaries were present at test. In fact, not even the adults exhibited significant categorical bias when boundaries were present during test (see Figure 9). 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.

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 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.

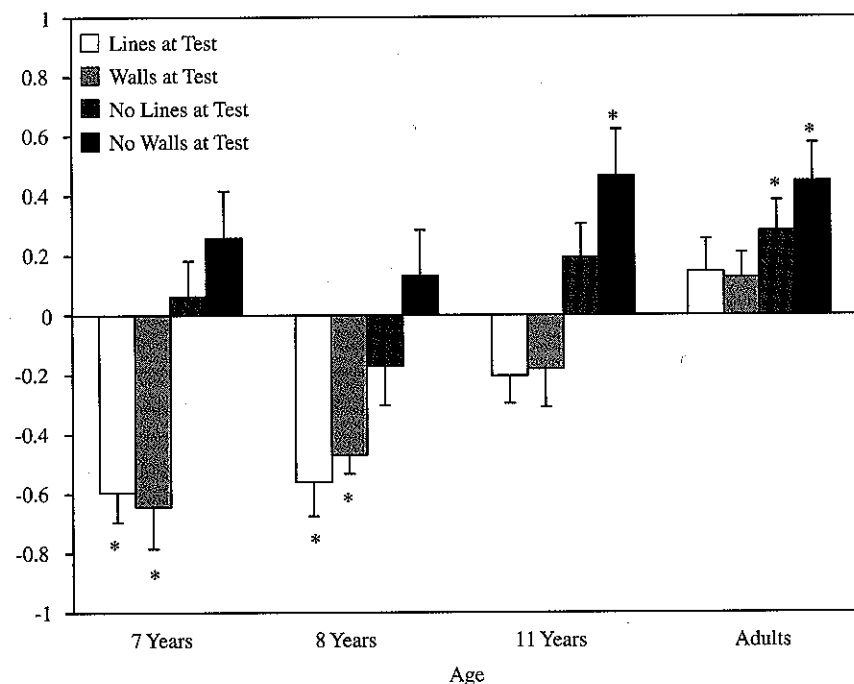


Fig. 9. Mean categorical bias by age when lines were present versus absent at test. Asterisks denote significant results ( $p < .05$ ) of one-sample  $t$ -tests comparing the displacement score to the expected score with no displacement. Positive scores reflect bias toward the category centers.

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. 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 in the moment out of the interaction of the memory representation and the available perceptual structure.

*d. Summary.* Taken together, the results of these studies illustrate the contention that 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 on categorical bias in estimates of location 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.

#### IV. Explaining the Emergence of Spatial Categorization Skills

In this section, I bring together these two lines of research on children's spatial categorization skills by addressing the question of how these skills emerge in the moment and over time. Clearly, ordering items based on common membership in a spatial group and placing objects from the same spatial group closer together than they really are depend critically on the ability to form and use spatial groups. And yet, forming and using spatial groups are not unitary skills that develop in an all-or-none fashion. As amply demonstrated throughout this chapter, such skills emerge in the moment depending on both age and task. With respect to the use of spatial categorization as an organizational device, children progress from using

spatial clustering strategies first to organize their searches, then to organize their directions and tour plans, and finally to organize their free recall. With respect to using spatial groups to remember object positions, adults almost always exhibit categorical bias at test when even a single cue (e.g., boundaries) is available to organize the locations into groups during learning. In contrast, children often do not exhibit categorical bias at test unless two cues were available during learning (e.g., boundaries and spatiotemporal contiguity).

In sum, the overall picture from these two programs of research is one of increasing reliance over development on spatial groups to organize object recall and remember object positions. It is especially noteworthy that adults consistently show more categorical bias in their estimates of location, despite the fact that adults almost always exhibit less absolute error in their placements than do children. This indicates that the "pull" from the spatial groups exerts an even stronger influence on adults' placements than on children's placements. Thus, adultlike performance in both recall organization and location memory is marked by strong reliance on spatial categories. Two key questions these findings raise are (1) What accounts for the age differences in spatial categorization skills observed across task contexts? and (2) How do developmental changes in spatial categorization skills come about?

#### A. THE EMERGENCE OF SPATIAL CATEGORIZATION SKILLS IN THE MOMENT

I start with the question of how age differences in spatial categorization skills emerge in the moment because this question sets the stage for thinking about how spatial categorization skills emerge over development. I propose that age differences in the moment emerge through the interaction of how well children represent and access spatial relational information (characteristics of the organism) and how explicitly tasks cue spatial relations among locations (characteristics of the environment). To form and use spatial groups, children must focus on the spatial relations among the locations. In other words, children must attend to which objects belong to the same spatial region or are in close proximity to each other. The ease with which children represent and access spatial relational information and the extent to which tasks cue spatial relations among locations impact the likelihood that children will form and use associations among locations based on common membership in a spatial group. I discuss these ideas in more detail below using examples from the research presented previously. Note that

organism and environment characteristics are considered separately in this discussion, with later commentary on how the two interact in the moment.

#### 1. Age Differences in Representing Spatial Relational Information

On the side of the organism, the ability to mentally represent information about the spatial relations among locations is critical for forming and using spatial groups. At a coarse-grained level, this involves classifying locations into groups based on spatial proximity and region membership. Such classification of locations into groups allows children and adults to form associations among locations within a group. Note that in both our studies of categorical clustering and categorical bias, children must notice which objects belong to the same spatial group despite the fact that they usually learn the objects in a random order. This is no small feat given the myriad of other relations children might attend to in these tasks. At a fine-grained level, the ability to mentally represent spatial relational information involves coding the distance and direction of locations relative to one other. Such coding of metric information about locations allows children and adults to remember groups of locations as spatial configurations.

What evidence is there that the ability to represent and access spatial relational information impacts categorical bias in children's placements? In a recent study, we examined how categorical bias at test was affected by opportunities to view objects together in time during learning (Recker & Plumert, 2007). Our previous work has consistently provided children and adults with many opportunities to simultaneously view the objects during learning. That is, participants cumulatively place the 20 objects on the floor of the box until they are all fully visible. We reasoned that it should be much more difficult to notice that particular objects belong to the same spatial group when they are seen in isolation as opposed to when they are seen together. If so, this would suggest that children have more difficulty than adults with mentally representing spatial relations among locations.

As in our previous studies, children and adults learned the locations of 20 objects marked by dots on the floor of an open, square box. The objects were always placed in a random order. In the simultaneous viewing condition, the objects were cumulatively placed on the floor of the box until all 20 objects were in their correct locations. Thus, after all objects had been placed, participants were able to simultaneously view the objects on the floor of the box. In the isolated viewing condition, participants were shown only one object in its correct location at a time. An object was placed in its location for approximately five seconds and was then removed by the



experimenter. Thus, the objects were never seen together in time. For both conditions, the dots marking the locations remained visible at all times during learning. Thus, opportunities to view the *locations* together in time remained constant across conditions, but opportunities to view the *objects* together in time varied across conditions. At test, participants replaced the objects without the aid of the dots.

In Experiment 1, we examined categorical bias in 7-, 9-, 11-year-olds' and adults' placements when two converging cues for forming spatial groups were present (i.e., lines divided the box into quadrants and the objects in each quadrant were categorically related). We found that 7-, 9-, and 11-year-olds and adults in the simultaneous viewing condition exhibited categorical bias. However, only the 11-year-olds and adults in the isolated viewing condition exhibited categorical bias, suggesting that younger children had much more difficulty forming strong associations among the locations when they viewed the objects in isolation. In Experiment 2, we examined categorical bias under simultaneous and isolated viewing conditions when only a single cue for forming spatial groups was present (i.e., the objects were categorically related but no boundaries were present). Eleven-year-olds and adults in the simultaneous viewing condition again exhibited categorical bias, but only the adults showed bias in the isolated viewing condition. Thus, 11-year-olds had more difficulty than did adults in forming strong spatial groups when they viewed the objects in isolation and only one cue defined the spatial groups. Finally, in Experiment 3 we examined categorical bias in adults' placements when boundaries were present but the objects were not related. Adults again exhibited bias in both the simultaneous and isolated viewing conditions. Together, these results indicate that the ability to represent spatial relational information is undergoing significant change over late childhood and early adolescence.

We can see how the ability to represent spatial relational information impacts children's use of spatial clustering strategies by comparing performance in tasks with differing representational demands. The study showing that 6-year-olds' directions were far less spatially organized than their searches even when all other aspects of the situation are equated is a good case in point (Plumert *et al.*, 1994). How might the representational demands of searching and direction giving affect the use of spatial organizational strategies? Although searching and direction giving both involve ordering locations, searching places far fewer representational demands on children than does direction giving. First, children can rely on the visible structure of the physical environment when searching for objects, whereas children have to mentally represent the structure of the physical environment when giving directions. In particular, children can use the

structure of the physical environment to constrain their movement while searching, but have to use their representation of the physical environment to constrain their imagined movement while giving directions. Clearly, relying on visually present environmental structure is far less taxing than relying on mentally represented environmental structure.

Second, children can use physical movement during searching to generate visual information about locations, whereas children have to use imagined movement during direction giving to retrieve information about locations. There is evidence indicating younger children have difficulty with representing imagined movement. For example, Gauvain and Rogoff (1989) found that not until nine years of age did children's descriptions of spatial layouts contain characteristics of a mental tour. Studies of developmental changes in children's use of elaboration also have shown that older elementary school children tend to generate dynamic images to help them remember information, but younger elementary school children tend to generate static images (Reese, 1977). The idea that using imagined movement to access spatial information plays an important role in efficient direction giving is further supported by the high frequency of movement references in adults' directions, suggesting that they spontaneously organized their directions as if they were guiding their listener on a walk through the house (e.g., "walk into the kitchen, pick up the toaster, and you'll find a piece hidden there"). In short, they used imagined movement as a mechanism for accessing their memory for the locations and for organizing their directions for finding the locations.

In sum, the ability to represent and access spatial relational information appears to play a key role in the age differences we see in children's spatial clustering strategies and categorical bias in estimates of location. To date, most of our work has focused on the ability to form associations among locations within a group rather than the ability to remember locations as spatial configurations. Clearly, research by Uttal and his colleagues has shown that children's ability to code and reproduce relative distance and direction in spatial configurations undergoes significant change from the preschool years through the elementary school years (Uttal, 1994, 1996; Uttal, Fisher, & Taylor, 2006; Uttal & Wellman, 1989). One interesting possibility that we are just beginning to consider is that coding the associations among locations in a spatial group and coding configural information about locations within a spatial group may work hand-in-hand to produce categorical bias in estimates of location. That is, coding spatial groups as configurations (i.e., creating a holistic representation) about may actually strengthen the associations among locations within a group, thereby leading to more, rather than less categorical bias. Preliminary work with adults suggests that this may be the case.

## 2. Task Differences in Cueing Spatial Relations among Locations

On the side of the environment, the extent to which the task cues spatial relations among locations also plays a critical role in forming and using spatial groups. Two basic principles are at work here. One is that some kind of environmental structure is necessary to group locations or subdivide spaces (even for adults), and the other is that more salient environmental structure makes it easier to group locations and subdivide spaces. This is clearly seen in our work on how cues for forming spatial groups during learning impact categorical bias in placements at test (Hund & Plumert, 2003, 2005; Hund *et al.*, 2002; Plumert & Hund, 2001; Recker & Plumert, 2007). First, it is noteworthy that even adults do not show significant categorical bias in their placements at test if no cues are available to group locations during learning (Plumert & Hund, 2001). In subsequent work, we further confirmed that categorical bias at *test* only occurs if cues are available for forming spatial groups during *learning* by having children and adults learn the locations without boundaries and then testing them either with or without boundaries (Recker, Plumert, & Stevens, 2007a). Both conditions resulted in the same low level of categorical bias. Thus, providing structure for grouping locations after the fact did not lead to categorical bias in people's object placements. Related work by Simmering and Spencer (2007) has also shown that adults are unable to mentally impose category boundaries unless they are tied to perceptually available environmental structure (e.g., axes of symmetry). Together, these studies provide strong evidence that thinking is not just about what is in the head.

Our work also shows that the salience of cues for forming spatial groups impacts spatial categorization skills. One indication that cue salience matters is the fact that children often require two converging cues for forming spatial groups in order to show significant categorical bias at test (Hund *et al.*, 2002; Recker & Plumert, 2007). The work described earlier on boundary salience also showed that children and adults exhibited more categorical bias when more salient boundaries (walls) were present during learning than when less salient boundaries (lines) were present. In other work, 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. There is also evidence indicating that boundary salience influences the order in which children organize their searches for objects (Nichols-Whitehead & Plumert, 2001). In particular, 3- and 4-year-olds' object retrieval was more spatially 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. Together, these results clearly show that the salience of environmental cues for forming spatial groups has a major impact on categorical bias in placements and use of spatial clustering as an organizational device.

We can also see how the extent to which the task cues spatial relations among locations plays a role in forming spatial groups by comparing spatial clustering in tasks that have similar representational demands but differ in how easily they draw children's attention to the spatial relations among locations. A good case in point is the study described previously showing that 10-year-olds exhibit much more spatial clustering when planning a tour of a set of objects than when recalling the names of a set of objects (Plumert & Strahan, 1997). An interesting feature of this study is that everything was the same in the tour-planning and free recall conditions until the moment children were given the memory test. Thus, the differences in 10-year-olds' tour plans and free recall can only be attributed to differences in how easily the two tasks drew children's attention to the spatial relations among the objects.

Why might this be the case? A task such as planning a tour of a set of objects may readily draw 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, 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. As seen earlier, 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). The tour-planning task may also have drawn children's attention to the spatial connections among objects because it activated children's meta-cognitive knowledge about tours. Although tours can be organized in many ways, they often involve taking the viewer from each location to the next closest location. Older children are more likely than younger children to have had experience with tours and hence may have a better understanding of the goals of tour planning. Other research has shown that children are more likely to deploy strategies to enhance recall or exhibit more sophisticated reasoning in tasks that contain a goal that is meaningful and familiar to them (Gauvain, 1993; Gauvain & Rogoff, 1986; Woody-Ramsey & Miller, 1988; Woolley, 2006). For example, Woody-Ramsey and Miller (1988) found that 4- and 5-year-olds were much more likely to use a

selective attention strategy when the task was embedded in the context of a meaningful story.

### 3. *Organism–Environment Interactions in the Moment*

The preceding discussion necessarily separates what the child and the environment contribute to the emergence of spatial categorization skills. Yet explaining the patterns of recall organization and categorical bias observed in these studies clearly requires a consideration of how the two interact at any moment in time. In fact, just knowing the extent of the child's ability to represent spatial relational information or the extent to which the task cues spatial relations among locations will not allow one to accurately predict patterns of recall organization or categorical bias. This is clearly illustrated in the many studies showing that age interacts with the task. For example, our recent work on age differences in children's ability to form spatial groups under isolated versus simultaneous viewing conditions has shown that the ability to form strong spatial groups under isolated viewing conditions is not an all-or-none ability (Recker & Plumert, 2007). Rather, 11-year-olds form strong spatial groups when converging cues define the spatial groups (i.e., visible boundaries and categorical relatedness), but not when only a single cue defines the spatial group (visible boundaries). Likewise, our work comparing spatial clustering in children's tour plans versus free recall shows that the tour-planning task is effective in eliciting strong spatial clustering in 10-year-olds, but not in younger children (Plumert & Strahan, 1997). Again, these findings underscore the idea that age differences in thinking can only be understood as emerging out of a system that includes both the child and the environment.

One general theme that has emerged from both lines of work is that children are able to exploit more subtle cues for forming and using spatial groups as they grow older. What implications does this have for the general argument made throughout this chapter? One possibility is that thinking resides more and more firmly "in the head" as development proceeds. In other words, the environment becomes less and less important for children's thinking as they grow older. Interestingly, many theories either implicitly or explicitly accept this idea about cognitive development. For example, Piaget's entire theory of cognitive development was based on the idea that children progress from strong to minimal reliance on the environment to guide their thinking as they move from the sensorimotor period to the formal operations period. Intuitively, this characterization of children's cognitive development seems right. But I would contend that the environment is always a part of thinking, even for adults. One way to think about this is that the coupling between the cognitive system and the

physical, task, or social environment becomes more finely tuned with development (and experience). Although speculative at this point, this tighter coupling might result from reduced variability and greater stability of bottom-up processes such as memory and attention, and from greater top-down control from executive centers and long-term memory. The end result is a greater sensitivity to more subtle environmental structure over learning and development.

## B. THE EMERGENCE OF SPATIAL CATEGORIZATION SKILLS OVER DEVELOPMENT

I turn now to thinking about how spatial categorization skills might emerge over longer time scales. As outlined at the beginning of this chapter, we need to think about cyclical organism–environment interactions over time in order to understand how skills emerge over development. In particular, we need to think about how the organism and environment characteristics proposed to play a role in the emergence of spatial categorization skills in the moment interact over time through the medium of experience. This way of thinking about developmental changes rests on a fundamental continuity between real-time and developmental processes (see also Elman *et al.*, 1996; Thelen & Smith, 1994). The same aspects of the cognitive system and the environment that work together in real time to produce age differences in thinking also work together over longer time scales to produce developmental changes in thinking (for an example of real-time change during short-term learning experiences, see Recker *et al.*, 2007b).

I propose that two complementary processes are at work to produce developmental change in use of spatial clustering strategies: (1) exposure to salient cues that highlight the spatial relations among locations leads to increases in children's ability to represent spatial relational information; and (2) increases in children's ability to represent spatial relational information allows children to notice less salient cues that highlight spatial relations among locations. What evidence is there that these two processes are actually at work? At present, the kinds of changes hypothesized to occur have only been investigated over very short time scales (i.e., within the course of an experiment). The general approach that my colleagues and I have taken is to examine whether experiences with using spatial clustering in a more supportive task lead to increases in the use of spatial clustering in a less supportive task. By supportive, I mean here tasks that highlight the spatial connections among objects (i.e., common membership in a spatial region and/or distance and direction of locations relative to one another). For example, we found that when 6-year-olds were allowed to search for

objects before giving directions for finding them, they exhibited high levels of spatial clustering in their subsequent directions (Plumert *et al.*, 1994). These results suggest that although children apply their spatial clustering skills to searching before they apply those same skills to direction giving, 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 (see Figure 10). 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 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, over the short-term time scale of an experiment, we see that experience with using spatial clustering in a more supportive task leads to transfer of spatial clustering to a less supportive task.

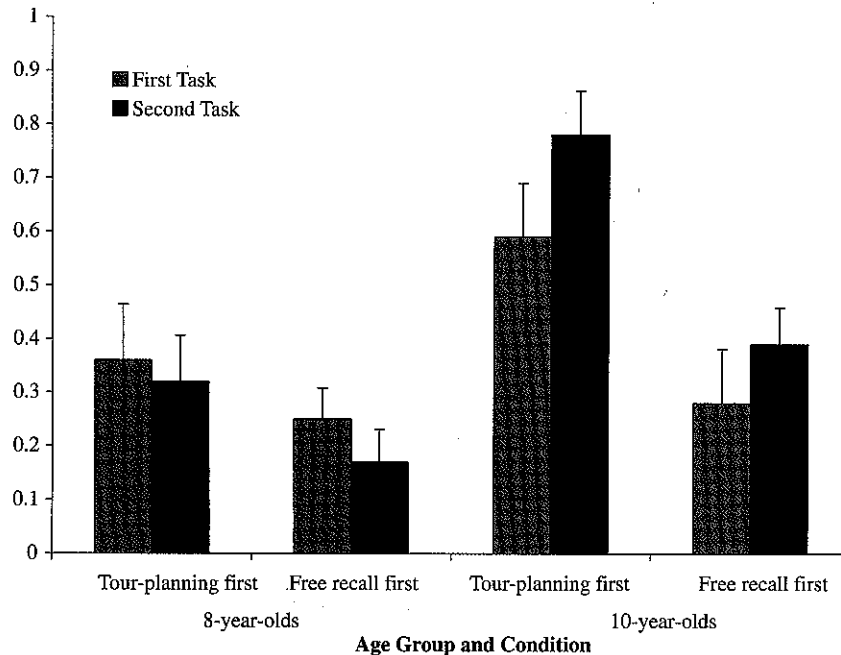


Fig. 10. Mean spatial clustering scores by age and condition in the first and second tasks.

Research in other domains of cognitive development also has shown that short-term experience with using a skill in a simpler task facilitates children's ability to use that skill in a more difficult task. Marzolf and DeLoache (1994), for example, found that 2½-year-olds were more likely to succeed on a difficult scale model task if given a simpler scale model task first. They argue that experience with the simpler task sensitized young children to the symbolic relations between the scale model and the real space. These findings are also consistent with the literature on analogical reasoning showing that young children are capable of transferring a solution to a more difficult problem if given experience with solving a simpler problem first (Brown, 1989; Gentner, 1989). In a similar vein, Newcombe and colleagues have shown that 3-year-old children integrate features (e.g., colored walls or large objects) with room geometry (e.g., length of walls) to reorient in larger, but not smaller spaces (Learmonth *et al.*, 2007). However, 3-year-olds do integrate features and geometry to reorient in a small space if given experience with reorienting in a larger scale space first. Similar findings have been recently reported by Twyman, Friedman, and Spetch (2007). Together, these results suggest that short-term experiences with solving specific problems in supportive environments sensitizes children to critical features of the problem, thereby affecting how children solve those same problems in less supportive environments.

Although these transfer studies are promising, our understanding of how change occurs over longer time scales is clearly limited. One missing link here is that changes in children's ability to represent spatial relational information are inferred, not directly tested. If experiences with using spatial clustering in more supportive task contexts sensitizes children to the spatial connections among objects, this should be evident in tests of children's spatial relational knowledge as well. A second problem is that most of these studies document near transfer rather than far transfer. For example, in the study showing that 10-year-old children were more likely to use spatial clustering to organize their free recall if given experience using spatial clustering to organize their tour plans first, the same dollhouse and objects were used in both tasks. Thus, we do not know whether the experience of using spatial clustering in the more supportive task would transfer to the less supportive task if children were learning the locations of a new set of objects in a new space. A third problem is that these studies are looking at transfer over very short time periods. More work is needed to determine whether the changes we see in the short term are the same kinds of changes we see over longer time periods. Microgenetic studies of change would be a useful step in this direction.

Finally, we might ask to what extent does 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 also Newport, 1990).

## V. Limits and Conclusions

What are the limits of this approach to understanding cognition and cognitive development? One is that in order to study the interaction of the child and the environment, we often end up separating the two. Although this reductionist approach may be necessary on a practical level for doing scientific research, one need not appeal to reductionism at a theoretical level for explaining cognitive development. Another potential problem is accurately identifying the kinds of environmental structure that matter in children's everyday lives (Oakes, Newcombe, & Plumert, in press). Given that children could attend to many different aspects of the physical, social, and task environment to in the real world, how do we determine which ones actually matter? Although we can make some theoretically informed guesses, progress on this front probably requires more back-and-forth between laboratory-based and real-world studies than is typically the case (Liben & Myers, 2007). Finally, if all thinking emerges out of the interaction of some aspect of the cognitive system and some aspect of environmental structure, doesn't this lead to an infinite regress? For example, if spatial categorization skills depend in part on the child's ability to mentally represent spatial relational information, where does this ability come from? Though infinite regress is theoretically a problem, a pragmatically sensible solution is to identify a behavior of interest and then determine how the components of the cognitive system and the

environment work together to produce the behavior in the moment and over development, at the same time acknowledging that the components themselves are emergent products of organism-environment interactions occurring at other levels of the system.

In closing, I have argued that variations in children's thinking across different contexts arise out of the real-time interaction of the cognitive system and the available environmental structure. From this perspective, thinking does not reside only in the head. Rather, thinking is an activity that emerges out of a unified system that includes both the child and the environment. Development proceeds in a cyclical fashion with changes in the cognitive system opening up new sensitivities to environmental structure, and new sensitivities to environmental structure leading to the further refinement of cognitive skills. Ultimately, a better understanding of these interactions both in the moment and over development should allow us to better predict the course of cognitive development for individual children and to successfully intervene when aspects of cognitive development go awry.

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