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Language and the Development of Spatial Reasoning

Human adult thought appears to transcend animal and infant capabilities greatly. In this chapter, we explore the possibility that language learning provides a path to mature cognition, focusing on the domain of spatial reasoning to probe questions about innate structure and conceptual change. We first summarize evidence that aspects of early spatial cognition rely on modular systems that exhibit characteristic limits in infants and animals. We then discuss how language could serve to overcome these limits.

Do human and animal minds consist of a collection of domain- and task-specific, encapsulated systems, or do they center on a single, central capacity for coordinating information and planning actions? In either case, are human cognitive capacities relatively constant over ontogeny, or do they change qualitatively with development and learning? Finally, are humans' cognitive systems shared by other animals, particularly nonhuman primates, or are certain systems unique to us?

This chapter has two faces. On the one hand, we argue that human and animal minds indeed depend on a collection of domain-specific, task-specific, and encapsulated cognitive systems: on a set of cognitive "modules" in Fodor's (1983) sense. These systems are largely constant over human development: they emerge in human infancy and undergo little qualitative change thereafter. Such core knowledge systems underlie many aspects of human cognition, from attentive tracking of objects (Carey & Xu, 2001) to estimation of numerosity (Dehaene, 1997) to representation of agency and intentionality (Johnson, 2000). Moreover, these systems are largely shared by humans and a variety of nonhuman animals, suggesting that they evolved before the differentiation of the human species. They link the

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sophisticated cognitive achievements of human adults to those of humbler creatures lacking language, culture, or education.

On the other hand, we argue that human and animal minds are endowed with domain-general, central systems that orchestrate the information delivered by core knowledge systems. One such system, associative learning, is common to human adults, infants, and nonhuman animals; it allows organisms to adapt their behavior to long-term regularities in the environment. A second system, however, is unique to human children and adults: the language faculty and the specific natural languages whose acquisition the language faculty supports. The latter system provides a medium that human children and adults use to combine information rapidly and flexibly, both within and across core domains.

Natural language has two properties that make it a good candidate mechanism for supporting interaction across conceptual domains. First, natural language has the flexibility to name concepts in any domain: "think" or "want" in theory of mind, "left" or "long" in the domain of space, "cup" or "on" in the domain of object mechanics. Second, natural language has the combinatorial structure to enable concepts from separate domains to be conjoined in phrases and sentences, for example, "I think he wants the cup that's to the left of the newspaper." Uniquely human combinatorial capacities that bind together information common to humans and other animals have previously been proposed to account for various aspects of cognition, including knowledge of the physical world (Carey & Spelke, 1994), knowledge of number (Spelke & Tsivkin, 2001), and theory of mind (de Villiers & de Villiers, 2003). Here we focus on the domain of spatial cognition, specifically the case of spatial reorientation (Cheng, 1986; Margules & Gallistel, 1988). We present evidence that language provides a mechanism by which children overcome limits to their core mechanisms for spatial representation. The hypothesis that language learning supports the development of spatial cognition has been spelled out previously (Spelke, 2003); the research presented here both tests this position and probes the mechanisms by which language might give rise to uniquely human representations of the spatial layout of the environment.

This chapter is divided into three parts. First, we review the literature on spatial reorientation in animals and in young children, arguing that spatial reorientation bears the hallmarks of core knowledge and of modularity. Second, we review studies of older children and adults, arguing that human spatial representations change qualitatively over development and show capacities not found in any other species. Third, we present two new experiments investigating the role of emerging spatial language in uniquely human navigation performance.

1 The Case of Spatial Reorientation

Many navigating animals can represent their own changing locations by integrating information about position, direction, and speed (e.g., Mittelstaedt & Mittelstaedt, 1980; Müller & Wehner, 1988). Because these computations are subject to cumulative errors, animals need to correct their sense of position and orientation by drawing on environmental representations in memory (Gallistel, 1990). The process of error correction, or *reorientation*, has been documented in a wide range of animals and serves to reveal what aspects of space animals and humans encode, remember, and use to regain their bearings.

1.1 *Comparative Studies on Reorientation*

In the earliest reorientation studies, food-deprived rats were shown the location of a food reward near a corner of a rectangular room with numerous visual and olfactory cues (Cheng, 1986; Margules & Gallistel, 1988). The rats were removed from the room, disoriented, and then returned to the room and allowed to search for the food. Rats searched equally at the target corner and at the corner located at a 180-degree rotation from the target, a location that had the same *geometric* relationship to the shape of the environment as the target location (fig. 6.1). Surprisingly, the rats did not use any of the nongeometric cues, such as the distinctive odors, brightnesses, scents, or textures in different regions of the environment, to distinguish between the two geometrically equivalent choices.

Importantly, rats failed to reorient by nongeometric information even though they detected the information, remembered it, and used it in other ways to guide their navigation. For example, Cheng and Gallistel noted that oriented rats readily learn to forage at a location marked by a panel of a distinctive brightness, pattern, or odor (e.g., Suzuki et al., 1980). They speculated that nongeometrically defined landmarks serve as direct cues to significant environmental locations, but not as cues to reorientation. In a preliminary test of this hypothesis, Cheng (1986) trained rats to forage at a position marked by a landmark. After disorientation in a rectangular room, the rats searched for food primarily at the correct, trained location. Cheng speculated that their search was guided by two independent processes: a reorientation process based exclusively on the shape of the room, and a landmark process based on a learned association between the nongeometric cue and the goal location.

Subsequent research has replicated Cheng's training effect in a variety of species: disoriented rhesus monkeys (Gouteux et al., 2001), rats (Dudchenko et al.,

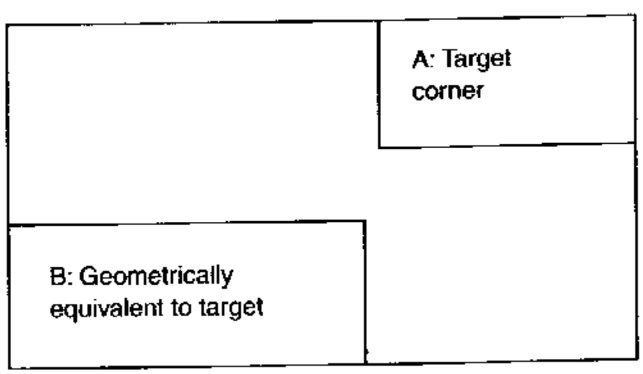

FIGURE 6.1 Schematic of the geometric effect in reorientation in a rectangular room. An object is hidden in the target corner (Corner A) while the subject watches. Following the disorientation procedure, there is no way to distinguish between Corner A and Corner B since they are located at rotationally symmetrical points (both are to the left of a short wall).

1997), and fish (Sovrano et al., 2002, 2003) have all been found, after training, to locate food in accordance both with the shape of the room and the position of a direct, nongeometrically defined landmark. Further evidence suggests that escape tasks engage landmark-based navigation processes more than otherwise identical foraging tasks. For example, Dudchenko and colleagues (1997) found that rats trained in a water maze (an aversive escape paradigm) learned to use landmark cues to find an underwater platform, even though they failed to do so in a foraging task equated for complexity, apparatus size, and amount of training.

Some investigators have argued that these data undermine Cheng and Gallistel's claim for a modular reorientation process (Gouteux et al., 2001; Dudchenko et al., 1997), but recent studies with fish, using an escape task, dramatically support the argument for two distinct processes (Sovrano et al., 2003). Disoriented fish were trained to find the escape door to a tank that, like the chamber Cheng used with rats, was rectangular in shape and was furnished with distinctive landmarks at each corner. After training, fish found the door effectively, using the landmarks. To determine how this information was used, the authors ran further tests in which they removed one or more landmarks. When all landmarks were removed, fish searched primarily and equally at the two geometrically appropriate doors, providing evidence that they used the shape of the environment to reorient themselves. But how does the presence of landmarks enhance performance further, distinguishing the correct door from its opposite? If landmarks were used for reorientation, the authors reasoned, then landmarks should enhance performance regardless of their spatial relation to the goal. In contrast, if landmarks were used to mark the goal position directly, only landmarks near the goal should enhance performance. Consistent with the second prediction, fish searched correctly when the landmarks far from the escape door were removed, leaving only the landmark near the escape door. However, they searched exclusively based on geometry when the landmark nearest the escape door was removed, leaving only the indirect, distal landmark. These findings and similar findings with monkeys (Couteux et al., 2001) provide strong support for Cheng's original hypothesis: navigation depends both on a reorientation mechanism that is sensitive to the shape of the environment and on associative learning mechanisms that link significant locations with nearby landmarks.

In sum, there is strong evidence for a reorientation mechanism with clear signature limits: it is sensitive to the shape of the extended surface layout but not to other detectable kinds of environmental information. Two types of situations allow disoriented animals to navigate by nongeometric information: training tasks and aversive escape tasks. The weight of the evidence suggests, however, that the same reorientation mechanism, focusing on geometric cues, operates in these situations, and that its signature limits are bypassed by associative learning of direct links between a goal location and a nearby landmark. Many animals, therefore, can represent both the shape of the surface layout and significant locations in the layout, and each type of representation guides a distinct navigation process. But can these distinct processes be flexibly combined into a single, unitary representation? In many studies to date, rats, monkeys, and fish have shown little ability to combine geometric with nongeometric features of the environment.

1.2 *Developmental Studies of Reorientation in Humans*

Children, like rats, reorient using the geometric features of the environment while ignoring salient nongeometric landmarks (Gouteux & Spelke, 2001; Hermer & Spelke, 1994, 1996; Wang et al., 1999). Borrowing from the paradigm of Cheng and Gallistel, Hermer and Spelke (1994) tested adults and 18- to 24-month-old children in a rectangular room with either all white walls or three white walls and one blue wall. Subjects watched a toy being hidden in one of the corners of the room. They were disoriented by being spun around with their eyes closed and were then asked to find the hidden toy. In the all-white-wall condition, where there were only geometric cues available for reorientation, subjects searched equally in the correct and in the geometrically equivalent corners. In the blue-wall condition, adults readily used the blue wall as a landmark to search only in the correct corner. Children, however, performed like rats: they searched equally in both geometrically correct corners, failing to use the presence of the blue wall to restrict their search to the correct corner.

A series of controls ensured that children's failure occurred specifically when the navigation task required that they use nongeometric features to *reorient*. Like rats, children succeeded in attending to, remembering, and using such features when they served as a direct cue to a significant location. In one set of studies, for example, children played a game in which a xylophone would play each time they hit a distinctively colored wall. Some children were brought in for multiple visits to make the colored wall especially familiar. When children were disoriented and encouraged to make the music, they moved directly to the colored wall, indicating that they attended to it, remembered it, and used it to guide their spatial behavior. When, however, the children were asked to retrieve the hidden object, their search was not affected by the location of this wall. Like rats, children used a nongeometric landmark as a direct cue to a significant location but not as a cue for reorientation (Wang et al., 1999).

Another set of experiments established that this behavioral reliance on geometric cues was specific to the reorientation task. Two containers, each with a unique pattern and color scheme, were located in two corners along one wall of the rectangular room. Children watched a toy being hidden in one of the containers and then closed their eyes as the containers were quietly moved. Children who were disoriented while their eyes were closed searched for the toy in the container with the geometrically congruent location but incorrect visual features. Children who remained oriented while the containers were moved chose the geometrically wrong but visually correct container. When children were taken outside of the rectangular room to make their choice, both oriented and disoriented children chose the visually correct container more often. These results indicate that all of the children had encoded the visual patterns of the correct container but that these cues were unavailable to the cognitive system responsible for reorienting in the rectangular room (Hermer & Spelke, 1996).

Taken together, the studies on rats, children, and adults suggest that humans possess a mechanism for reorientation that is shared with other mammals and that uses geometric information about an environment while ignoring salient nongeometric cues. One incidental finding from the studies of adults suggests that the knowledge delivered by this system is not explicitly accessible: asked how they chose where to search for the hidden object, adults readily referred to the nongeometric landmark when it was available but rarely referred to the shape of the room. Indeed, some adults, after searching exclusively at the two geometrically appropriate corners, maintained that they had searched the four corners at random, simply following a "hunch" about where the hidden object might be. These incidental findings are consistent with Cheng's hypothesis that reorientation depends on an encapsulated system of representation.

1.3 A Geometric Module?

Although an abundance of evidence suggests that reorientation depends on an encapsulated process, some evidence from children suggests that geometry is not the critical property that determines what information is, and is not, accessible to that system. Learmonth, Nadel, and Newcombe (2002) replicated Hermer and Spelke's original finding with four-year-old children, providing evidence that children fail to use nongeometric information in the reorientation task in a small room, but demonstrated that the same children succeed in a room four times as large. However, room size in this experiment was confounded with at least two other factors, landmark distance and landmark size; the landmark in the large room was both larger and farther away from the reorienting child. A recent study demonstrated that the factor of landmark distance may explain the room size effect. Two-year-old children clearly were shown to use a distant nongeometric cue—a light source outside the small room—as a cue for reorientation (Dibble et al., 2003). Therefore, information about the shape of the environment is not always necessary for reorientation, because a distant light source can serve the same function.

Further experiments provide evidence that geometric information is not always sufficient for reorientation. Gouteux and Spelke (2001) tested four-year-old children in a large circular chamber with four indistinguishable landmarks placed in the same locations as the four corners of Hermer and Spelke's original rectangular room. Although the geometric configuration was the same as in past studies, children failed to reorient by this configuration of landmarks. Across a series of studies testing children in a rectangular configuration, children reoriented in accord with the shape of extended surfaces in the layout but not in accord with the shape of an array of objects.

A recent study qualifies the claim of a geometric module still further. Hupbach and Nadel (2003) tested two- to four-year-old children in a rhombus-shaped room: its four walls were equal in length but met at obtuse and acute angles. Although the major and minor axes of this room differed as dramatically as those in Hermer's original studies, the younger children failed to reorient by this difference. After observing an object hidden in an acute-angled corner, for example, they were equally likely to search at the corners with obtuse and acute angles. Although children's reorientation is affected by the differing lengths of the walls of a chamber, it evidently is not affected by the differing angles at which those walls meet.

Taken together, these findings suggest a reconceptualization of the "geometric module" as an encapsulated and task-specific mechanism that analyzes large, stable, three-dimensional features of the surface layout. Many researchers have argued that these features are the most dependable for navigating animals in natural environments (e.g., Biegler & Morris, 1993; Gallistel, 1990; Hermer & Spelke, 1996; Learmonth et al., 2002). Hills and oak trees are likely to maintain their size and geometric configuration over time, whereas the positions of snow patches, colors of the leaves, and location of small rocks do not. Although the findings suggest a different picture of how and why geometry is privileged in reorientation, they do not damage the notion that the reorientation process is modular or lessen the gap between the reorientation performance of animals and young children on the one hand and adults on the other. After all, a human adult *can* navigate using visual cues of any size and nature, spontaneously and on the first try. This ability is likely to depend on mechanisms that allow the spatial representations available to the reorientation module to interact with other conceptual domains. (See Carruthers, chapter 5 here).

In sum, many aspects of reorientation across a number of species, including young humans, bear the hallmarks of modular processing, such as a task-specific reliance on geometry and an encapsulated imperviousness to many kinds of sensory cues. This conclusion raises a question: Why do human adults perform so differently in reorientation tasks?

1.4 *The Language Hypothesis in the Development of Spatial Representations and Reorientation*

The studies just outlined provide a starting point for considering which capacities for spatial representation are present in human adults but not in children and rats. Cheng and Gallistel's rats, as well as Hermer and Spelke's 18- to 24-month-old children, demonstrated an ability to represent and use a concept like *left of the long wall* in locating objects. Using a geometric notion like *left of the long wall* to reorient would yield two answers in a rectangular room with two long walls. However, rats and children failed to encode a concept like *left of the red wall*, a concept that unambiguously selects the correct location but requires the use of the nongeometric feature *red*. Thus, it seems that both children and rats can represent concepts like *red wall* and geometrically defined locations like *left of the short wall*, but they cannot encode combined concepts like *left of the red wall*.

One of us has hypothesized that the acquisition of a specific, natural language allows humans to combine distinct conceptual domains of core knowledge (Spelke, 2003). On this view, the reorientation module is an innately specified, domain-specific cognitive system shared among humans and other animals. Because children and rats distinguish between the corners with a short wall on the *left* and the corners with a short wall on the *right*, this module is sensitive to sense relations (i.e., the difference between *left* and *right*) and thus contains the concepts *left* and *right*. A different system, perhaps an object-processing system, might represent the presence of a red wall and thus contain the concepts *red* and *wall* or even *red wall*. Without language, however, the only domain-general system available to combine these diverse concepts is the system of associative learning. Associative learning processes would allow an animal or child to learn gradually to search *both left of a long wall and at a red wall*. In the absence of extended learning, however, there is no way to bridge the separate concepts *left* and *red wall;* only language provides the syntactic structure enabling a combined concept *left of the red wall.*

Before these studies, two lines of evidence suggest that language indeed plays a role in the developmental change in reorientation performance. First, the age at which children begin to use landmarks to reorient highly correlates with their accurate production of the phrases *left of* X and *right of* X (Hermer-Vasquez et al., 2001). This correlation suggests a connection between linguistic ability and the conceptual underpinnings of successful navigation by landmarks. By contrast, no other aspects of cognitive development that were explored, such as spatial and verbal working memory, IQ, and vocabulary size, significantly correlated with performance on reorientation tasks.

The second line of evidence comes from adults. When adults do a verbal interference task at the same time as the reorientation task, they fail to use landmarks, suggesting that access to the language system is necessary to perform the task correctly. By contrast, when adults are asked to shadow a rhythm instead of words, they succeed in using the colored wall to reorient (Hermer-Vasquez et al., 1999). Adults' superior performance during the rhythm shadowing task is probably not attributable to the greater difficulty of the verbal shadowing task, since a set of parallel studies suggested that the rhythm shadowing condition was at least as difficult. Importantly, these studies revealed that verbally shadowing adults both used the shape of the room to reorient and used a nongeometric landmark as a direct cue to the hidden object's location. Verbal interference specifically impaired adults' ability to use the nongeometric information in the reorientation task.

While both of these findings suggest that language is involved in the developmental change in spatial representation described here, neither provides a direct, causal link between language acquisition and novel conceptual combination. Concerning the developmental correlation between "left" and "right" production and reorientation performance, correlation does not imply causation. The child's spatial representations may change first, enabling better reorientation performance, and fostering the acquisition of spatial language. Indeed, there is no intuitive reason why language should precede conceptual change; it is just as likely that a purely nonlinguistic maturation in spatial cognition would make the terms *left* and *right* meaningful in a way that they weren't before, enabling the child to learn these terms.

The verbal interference studies with adults also fail to show that language acquisition causes the change in spatial cognition. Mature cognitive systems are considerably different from those of two-year-old children: adults have years of practice sharing spatial concepts with each other through language, and a large body of data in various domains suggests that habitual patterns of language use have cognitive consequences for nonlinguistic tasks (e.g., Boroditsky & Schmidt, 2000). Adults' extended use of language, therefore, may promote more verbalized spatial representations than those of children. Adults might even construct a completely different representational system for reorientation from that of children. Consequently, verbal interference may impair adults' navigation, even if language played no role in the initial acquisition of the spatial representations that are uniquely human.

In an attempt to address these alternative explanations for the apparent involvement of language in reorientation tasks, we have embarked on two studies of the effect of language on children's navigation and spatial representation. The first study investigates whether the presentation of linguistic information alters children's attention to, memory for, and use of nongeometric information in a navigation task. The second study investigates whether training in spatial language can enhance children's landmark-based navigation and spatial representation.

2 Does Verbal Cueing Enhance Children's Use of Nongeometric Landmarks?

The point of departure for our first study is the finding that rats, fish, and monkeys can learn to use a nongeometric landmark as a direct cue to the location of a hidden object, allowing search for the object both in accord with the shape of the environment and in accord with the object's proximity to the landmark. In the studies with animals, subjects learned over a series of training trials to locate the hidden object at a particular landmark. It seemed possible, however, that linguistic communication could substitute for this kind of learning and facilitate an association between the reward object and the nongeometric landmark.

To test whether language might help children to explicitly represent, remember, and orient to the correctly colored wall, we conducted an experiment using a language cue (Shusterman et al., in prep.). The design of the study was very simple: During some trials, the experimenter said, while she was hiding the sticker, "Look! I'm hiding it by the red wall!" or "Look! I'm hiding it by the white wall!" If language can serve to direct attention and memory to task-relevant information in the ways that associative learning processes do, then the verbal cue should lead children to search for the object in the ways that trained rats and fish do, using room shape to reorient and using nongeometric landmarks as direct cues to the object's location.

We ran 16 experimental and 16 control subjects in this study, changing only the presence or absence of the verbal cue. All of the children participated in four trials of the reorientation task. The task was conducted in a four- by six-foot rectangular apparatus built according to the original specifications in Hermer and Spelke (1994), with three walls covered with white fabric and one of the short walls entirely covered with bright red fabric. The door was made of a loose flap of white fabric and could not be distinguished from the other walls when closed. Blue flaps hanging in each of the four corners served as hiding places for the stickers.

On each trial, children watched the experimenter hide a sticker in one of the four hiding corners. Then the child put on a blindfold and turned around slowly four to five times. Before removing the blindfold, the experimenter ensured that the child was truly disoriented (indicated by the child's inability to correctly point to the door). The experimenter turned the child to face a particular wall and removed the blindfold, and the child was allowed to search for the sticker. Each child saw the sticker being hidden in the same corner on all four trials. Equal numbers of children in each group were tested with each hiding corner. In the

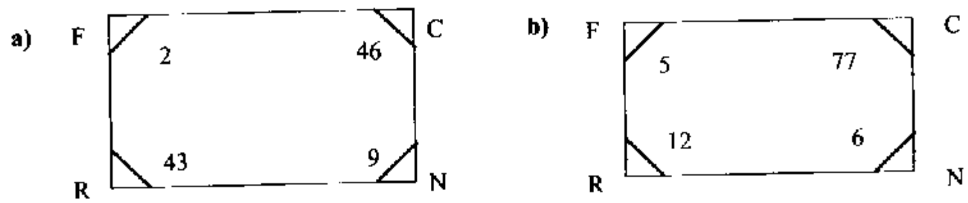

FIGURE 6.2 Mean search rates for a) control subjects ($n = 16$) and b) cued subjects ($n = 16$). Rates are expressed as percentage (%) of trials with first search at the corner. C: correct; R: rotated; N: near; F: far.

"cue" group, the experimenter told the child, as she was hiding the sticker, "Look! I'm hiding it by the red (or white) wall!"[1] In the "no cue" group, the experimenter talked with the child during the experiment but without explicitly referring to the color of the wall at the hiding place.

The verbal cue greatly enhanced children's performance on the reorientation task (fig. 6.2). In the no-cue condition, children showed the same geometric search patterns demonstrated in previous studies, choosing the correct corner and the opposite corner equally. In the verbal cue condition, by contrast, children relied both on the shape of the room and on the landmark.

This finding raises two questions. First, what navigation processes are engaged by talking about the nongeometric landmark? Studies of animals provide evidence that nongeometric landmarks are used as direct cues to a hidden object's location but not as cues for reorientation. Is the same true for the children in our study, or do children who hear that an object is being hidden at a nongeometric landmark actually reorient themselves by that landmark? Several incidental observations in this experiment suggest that children used the red or white wall as a direct cue to the object's location, not as a cue to reorientation. First, response latencies were longer in this study than in previous reorientation studies, suggesting that attending to the red wall elicited a further process not elicited by search in the rectangular room without landmarks. Second, children often appeared to hesitate, looking to both geometrically appropriate corners before choosing one. These observations are consistent with the thesis that two processes guided children's search: a reorientation process based solely on geometry and a landmark-guided process for selecting among the geometrically correct corners.

The second question is more speculative: if talking about the color of a wall allows children to use it as a direct cue to the hidden object's location, then why do children not provide themselves with this cue in the reorientation task? Peter Carruthers (personal communication, December 3, 2003) has offered an explanation why children may need to learn *left* and *right* in order to succeed independently in the reorientation task, even though the current studies show that *at*

1. While intuitively this might seem likely to have confused the children who heard a cue about the white wall, since there were actually *three* white walls (two long and one short), children immediately and correctly assumed that we were referring to the *short* white wall directly across from the short red wall.

would suffice. *Left of the red wall* specifies a unique corner in the room, while *at the red wall* does not, being ambiguous about which side of the red wall contains the toy. It does not make sense to remind oneself of a location with an ambiguous phrase, so children who don't know *left* and *right* don't encode the situation verbally at all. All this is a consequence (and a demonstration) of the deep encapsulation of the geometric information: because children, like adults, do not realize that they implicitly know which side of the red wall to search, they cannot use this fact in their explicit encoding and reasoning in the task.

We suspect that children also fail to encode and use the nongeometric cue spontaneously for the same reason that untrained animals do: because such cues are rarely as valid or useful as is the geometric information by which animals reorient. When animals are tested in symmetrical environments in which the shape of the surface layout provides ambiguous information, they learn over trials to supplement their normal navigation processes by attending to and using nongeometric information as direct landmark cues. Similarly, when children are told that an object is being hidden near a named, direct landmark, they incorporate this information into their search strategy. In the absence of either training or verbal cueing, however, animals and children fail to use this information.

If our speculations are correct, then neither rats who are trained to use a nongeometric landmark nor young children who hear talk about a nongeometric landmark truly combine geometric and nongeometric information into a unitary representation of an object's position. Adults, in contrast, do appear to form a single, unitary representation that combines these sources of information. When adults are disoriented in a rectangular room with a distinctively colored wall, they search immediately for objects in their correct locations, exhibiting none of the vacillations and hesitations shown by the children in our study. When asked why they searched where they did, adults typically report at once that they saw the object hidden, for example, "left of the red wall." Our next experiment was undertaken to provide more direct evidence for the hypothesis that language acquisition is causally related to this change in reorientation behavior. Specifically, we used a language training study to ask whether the acquisition of spatial language both precedes and gives rise to the developmental change in spatial representation and behavior.

3 Does Learning Spatial Language Change Reorientation Behavior?

In order to test the causal effect of language on reorientation, we taught children the words *left* and *right* and then tested their reorientation in a small rectangular room with a single nongeometric landmark, a red wall. Previous research has indicated that children under five typically fail to use landmarks in the reorientation task and that children begin reorienting successfully between the ages of five and six. Therefore, we chose to use children between four and four and a half years old for our study on the assumption that these children would fail to exhibit landmark-based reorientation behavior without any intervention, but that they would probably have the conceptual readiness to acquire the necessary knowledge for success in the reorientation task.

We created a language training protocol based on findings and intuitions in the literature on children's acquisition of spatial terms like *front* and *back* as well as *left* and *right* (Kuczaj & Maratsos, 1975; Piaget & Inhelder, 1948/1967; Rigal, 1994). It seemed likely to us that children learn these terms most easily on their own body parts. However, we were not sure that learning *left* and *right* on one's own body parts would be sufficient to affect reorientation behavior; after all, understanding the position of a moveable, hidden object relative to a landmark (in a thought like *the toy is to the left of the red wall*) seems qualitatively different and more difficult than identifying one's own left arm, which is much more stable than either a hidden object or a red wall landmark. Therefore, we used a combined training procedure that attempted to teach children to map the words *left* and *right* first onto their own bodies and then onto moveable objects placed at their sides.

The training procedure consisted of two comprehension games that followed an identical structure, the first focusing on body parts and the second focusing on objects. In the body parts game, children stood in the center of the room and followed instructions like "raise your right arm" or "shake your left leg," interspersed with filler commands like "touch your toes." In the objects game, children stood in the center of the room with four objects around them (in front, in back, and at their sides) and were asked to "show me the one on your left" or "give me the toy on your right," with filler trials asking for the object in front or back of the child or referring to the object by color. Both language games followed the same basic structure of pretest, feedback training, and posttest.

Children were observed over two sessions, typically a week apart. In the first session, children participated in our language training procedure, preceded and followed by tests of comprehension of the terms *left* and *right*. The second session began with language posttests to see whether children remembered what they had learned in the first session training. Then children walked to a separate room with a reorientation chamber and participated in up to eight trials of the reorientation task. Additional children were tested only in the reorientation experiment and never participated in language training.

Our first finding is that it is possible to teach some children the terms *left* and *right* under the present conditions. Of the 19 children who participated in training and returned for a second session, 8 passed both comprehension tests at the start of the second session. Thus, about 40 percent of the children demonstrated an improved comprehension of the terms *left* and *right*. (See table 6.1.)

How did language training affect children's behavior in the reorientation room? To address this question, we classified all of the subjects into one of two groups on the basis of their second session language assessments. The 8 *learners* passed both the body parts and objects games during the second session, and the 11 *nonlearners* did not. Consistent with the data from previous reorientation studies, both learners and nonlearners searched primarily in the two geometrically appropriate corners. Learners, however, searched in the *correct* geometric corner significantly more often than nonlearners. We also compared the reorientation behavior of learners and nonlearners to untrained controls who came into the lab for a single visit and participated only in the reorientation task. The behavior of control subjects was essentially identical to that of the nonlearners and significantly below the

TABLE 6.1 Numbers of subjects succeeding following training on two left-right tasks immediately after training (Session 1) and approximately 1 week later (Session 2).

	Session 1			*Session 2*	
	Participating in training	Participating in post-test	Passing post-test	Participating in check-up	Passing check-up
Body parts	22	21	14	19	11
Objects	18	11	6	17	10
Both games	18	11	6	17	8

Children who passed the pre-test are counted here as participating in pre-test and post-test and passing post-test. Passing is defined as 75% or more correct.

performance of learners. Figure 6.3 shows mean search rates for learners, nonlearners, and untrained controls.

The results confirm and extend the findings of Hermer-Vasquez and collaborators that knowledge of *left* and *right* correlates with higher accuracy in a reoriented search task. These findings provide the strongest evidence to date that the acquisition of spatial language closely mirrors the development of reorientation abilities within an individual child. At the same time, these results leave open a number of questions. One fundamental question is whether language training truly causes a change in reorientation performance. While our findings are consistent with this possibility, they do not rule out the possibility that the children designated as learners in our study might have succeeded on reorientation prior to our language intervention. Perhaps the children whom we classified as learners had advantages over the nonlearners in the reorientation task aside from the factor of language. For example, perhaps these children were simply better problem-solvers, and

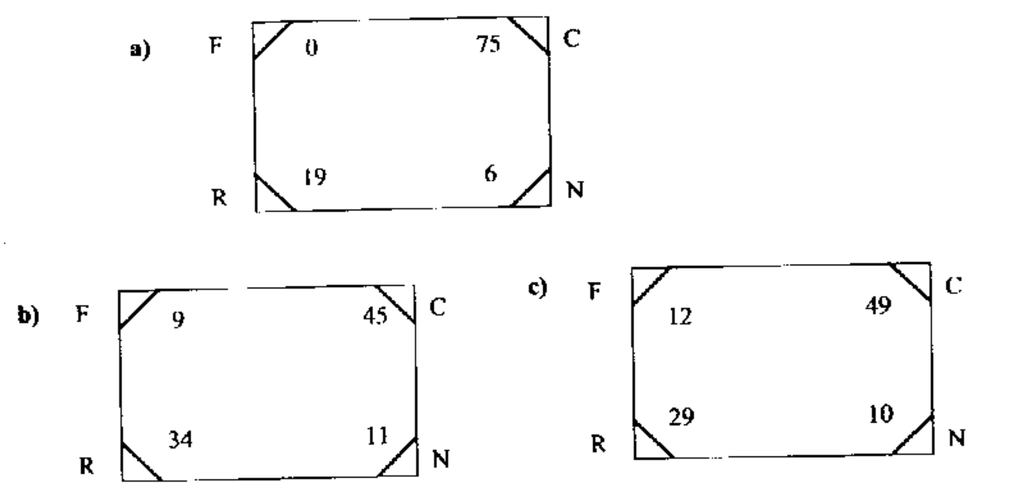

FIGURE 6.3 Mean search rates for a) learners ($n = 7$)*, b) non-learners ($n = 11$), and c) untrained controls ($n = 12$). Rates are expressed as percentage (%) of trials with first search at that corner. C: correct; R: rotated; N: near; F: far. *One of the 8 children as Learners refused to cooperate during the orientation task, so the 7 remaining children contribute to this analysis.

therefore succeeded at the language games and the reorientation game independently. Language would then have no causal role as part of the learning mechanism in this case.

On the basis of Hermer-Vasquez and colleagues' (2001) report that IQ and other general problem-solving measures failed to predict reorientation behavior, we doubt that this explanation is correct. Nevertheless, it is an alternative that we take seriously, and further work in the lab is aimed at better probing the causal direction of the demonstrated correlation between language learning and increased success on the reorientation task.

4 Developing Systems for Representing Space

If spatial language does cause a change in reorientation performance, what is the nature of this effect? We now turn to a discussion of possible mechanisms by which language could exert influence over spatial representation and reorientation.

4.1 *Linguistic Control of Attention and Memory*

According to the initial hypothesis motivating this study, language learning allows the contents of separate modules to combine via natural language syntax, enabling a new thought like "the toy is to the left of the red wall." Alternatively, language learning may enable a novel ability to reorient in some other way than what is proposed in this hypothesis, without combining information from isolated modules. In particular, language may draw attention to nongeometric information or make that information more memorable.

Our first experiment showed that language can indeed direct a child's attention to task-relevant information. However, there are reasons to suggest that the language training in our second experiment played a different role. First, the children who learned *left* and *right* tended to search for the object directly, performing like adults and showing none of the hesitations of the children in the earlier experiment, whose attention was drawn to the wall by naming it. Their direct search suggests that they formed a unitary representation of the object's position, combining geometric and nongeometric information. Second, nothing about the language training specifically mentioned or called the child's attention to the kind of landmark information present in the reorientation task. On the contrary, children were taught *left* and *right* in quite a different context from the environment available during the reorientation task.

There remain three further potential explanations for the apparent training effect in the second experiment. First, domain-general cognitive control systems, such as attention and memory, may have benefited from the training, for reasons unrelated to the linguistic combination hypothesis. One might argue that the initial representations appear encapsulated simply because they are too weak to interact with each other or to drive behavior (for example, see Munakata, 2001). Language learning might make existing knowledge more explicit by strengthening weak representations. Training a child to label explicitly a location might make the location less taxing to remember, allowing the child to hold onto the concept *left of the long wall* at the same time as the concept *red wall*. By making both representations explicit at the same time, a child might be able to reorient more successfully than before, without any significant role of natural language or any requirement that the initial representations were combined in any special way.

Second, spatial language training may enhance children's performance by drawing their attention to the relevant spatial relationships. On this view, the spatial relationships need to be noticed by the child, but they do not need to be represented linguistically. In this case, children might benefit equally from training in a nonlinguistic task that emphasizes the same spatial relationships.

Third, language learning may enhance children's navigation performance by helping them to perform a two-step computation: they orient to the short red wall or the short white wall (wherever the object was hidden), and they choose between the left and right corners based on geometric information. This computation does not require a combined concept; furthermore, children already have all of the ingredients they need to perform each step (which can occur in any order). And, most pointedly, the results of the verbal cueing experiment described earlier show that children are capable of behaving in this way. Nevertheless, we think it is unlikely that our language training on phrases with the words *left* and *right* somehow prompted children to perform the two-step computation. A critical step in this computation is to orient to the correct colored wall, a step that children dramatically *fail* to make before they have a rich understanding of left and right, despite the fact that the difference between the two walls is salient to them. Apparently, this step is not as trivial as it seems. Moreover, it is utterly mysterious why learning *left* would help a child pay attention to wall color.

The current training study does not rule out these three possibilities, but we find them less plausible than the hypothesis that specific properties of spatial language led to the results presented here. We now address this hypothesis in more detail.

4.2 *Linguistic Combination of Modular Representations*

We hypothesize that learning a particular linguistic structure (left of X) enables children to construct a unitary representation of a concept like *left of the red wall*. There are several ways to imagine the benefit of such a representation. On the linguistic combination hypothesis, concepts that were previously unusable for a particular task, like wall color in a reorientation task, become usable by virtue of their connection to information that is automatically used in the task, in this case a sense of *left* from the geometric module. On a variant of this view, learning a phrase like "to the left of the red wall" might help the child remember the red wall, because the concept *red* is only remembered (for the purposes of a reorientation task) when its status is elevated from a visual feature of the environment to a noun phrase in a combinatorial spatial description. Regardless of whether the critical role of language is to combine modular representations or to redescribe and make explicit otherwise unusable information, both suggestions share an underlying mechanism: the unitary representation of piecemeal concepts.

One question for the linguistic combination hypothesis is whether the proposed mechanism uniquely solves the reorientation problem, or whether it is simply one of many possible mechanisms that might underlie this developmental transition. We suspect that the majority of children end up learning via some version of the linguistic combination process, but there may be different paths to the same end. We would not be surprised if the occasional child found an alternative way to solve the reorientation game, as did trained animals and children in our first experiment. In fact, we think we have witnessed a handful of these children over the various experiments we have conducted. Nevertheless, the critical point about the linguistic combination hypothesis is *cognitive flexibility*. Language learning, in one fell swoop, affords the ability to solve many tasks. If children were taught, or discovered on their own, some mnemonic device for reorientation, it would probably not help them succeed on many other tasks. Teaching children *left* and *right*, however, is likely to help them succeed on a wide range of novel tasks. Therefore, even if language does not provide a *unique* solution to the reorientation problem, it arguably provides the *best* (i.e., most flexible) solution to the reorientation problem.

Another challenge for the linguistic combination hypothesis is specifying exactly how language promotes flexible navigation. If language helps to combine the contents of encapsulated systems, how do we know which contents are combined by what bits of language? According to the hypothesis as originally described (Spelke, 2003), the word *left* maps onto a sense relation available from the output of the geometric module; the words *red wall* map onto the output of the object processing system; and these concepts become combined by natural language into a coherent, unified phrase. But what exactly does it mean to learn *left*? Does the meaning of the word in the child's mind actually reflect the geometric content of a navigation-specific mechanism?

The data here and from other training studies conducted in our lab suggest that children map the words *left* and *right* onto body parts earlier and more easily than onto sensed spatial relations between objects (Shusterman & Spelke, unpublished data; Shusterman & Abarbanell, 2004). At the same time, a large body of work suggests that animals, including humans, simultaneously hold multiple language-independent representations of space (Colby, 1999), including multiple representations of sense relations (i.e., left and right). Two simple examples of representations that hold sense information are proprioception (the sense of one's own body in space) and the sense of left and right conveyed by the geometric module. What is the relation between the spatial representations used for word learning and those used in language-independent tasks? Which systems contain the sense relations that link up with the word *left*? These questions remain wide open. The linguistic combination hypothesis requires direct tests of the claim that the word *left* in fact captures some of the content of the reorientation module.

4.3 *Training Studies as an Approach to Exploring Learning Mechanisms*

We hope that this case study on developmental change in spatial reorientation can make a methodological contribution on possible roles of training studies, as well as an empirical contribution to the literature on conceptual development. In order to understand mechanisms of learning and conceptual change, psychologists need to describe adequately the initial state of representations, the computations performed by the learning mechanism, and the content of the representations arrived at by the learning mechanism. Training methodologies can speak to each of these questions.

Training studies grant insight into the initial state of representations by allowing researchers to compare the ease of learning various concepts. In cases where there is a discrepancy in children's ability to grasp different meanings of words, the meaning that is *easier* to learn might be presumed to be more conceptually available than meanings that are more difficult to learn. Through careful investigation of which meanings children adopt easily and not so easily, the conceptual structure of the preexisting, putatively isolated representations in core knowledge become more transparent. This approach takes word learning as a window into prelinguistic conceptual structure, and the relative ease of word learning as a mirror of prior conceptual availability. In other research, we have begun using this approach to understand something about how children initially represent and learn words like *left* and *right* (Shusterman & Abarbanell, 2004). This approach is notably not unique to this study (for example, see Gentner & Boroditsky, 2001; Macario, 1991). Ideally, these sorts of studies will help to determine the grain of individual concepts that might get joined in a combinatorial system, as well as the boundaries of the domains that house these concepts.

In order to understand the computations performed by children in instances of conceptual development such as the one here, various types of training can be worked out to reflect different theorized learning mechanisms. The success of any particular training method could then serve as an indicator of the match between the hypothesized learning process and the computations that actually go on in the minds of children in more natural learning experiences. In this way, training studies might be used in parallel with computational models of learning algorithms to assess the plausibility of any hypothesized learning mechanism. This approach has been used fruitfully in studies of children's learning of adjectives (e.g., Gasser & Smith, 1998).

Finally, in order to understand the extent of children's knowledge at the end of a learning process, one can use training studies to test generalization to untrained contexts. Reorientation might be seen as one kind of a test of generalization; if the linguistic combination hypothesis stands a chance of being correct, then we should be able to find other test cases that require conceptual combination mediated by the words *left* and *right*.

5 Summary

In this chapter, we explore the developmental shift in human reorientation, a process that appears to be modular in animals and young children, but not in adults. We also address some challenges to claims about modularity in reorientation and the role of language in conceptual combinations. We present empirical evidence in support of the claim that language plays a causal role in this developmental shift, and we argue that the specific role of language is to allow the isolated contents of encapsulated representations to combine into unified representations. In particular, we hope that by elaborating the process and consequences of spatial language acquisition, we will be able to elucidate the role of language in this developmental shift and extend these hypotheses and methodologies to other tasks and domains where adult competence transcends the bounds of core knowledge.