Developing Knowledge of Space: Core Systems and New Combinations

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Three Intuitions about Human Intelligence

People who reflect on their own cognitive capacities often share three intuitions. First, human thinking appears to be qualitatively different from the thinking of other animals. Second, human thinking appears to change qualitatively over development. Third, human thinking appears to depend in some way on language: our unique system for expressing thoughts somehow seems to make those thoughts possible.

In contemporary cognitive science, these intuitions have fallen on hard times. Behavioral biologists, comparative psychologists, and neuroscientists have found homologies between the representational systems of humans and other animals in numerous domains, including vision, object recognition, attention and working memory, and action planning. These homologies challenge those who believe any gulf divides human from nonhuman cognition. Studies of children have revealed striking continuities over human development: constant, core capacities to represent space and number, reason about objects and people, and engage in coordinated, goal-directed acts. These findings suggest that developmental changes in children's thinking stem more from the elaboration of core knowledge systems than from the emergence of new systems. Finally, studies of people with language impairments reveal rich and elaborate representations of the environment, indicating that the capacity to think does not depend on the capacity to express one's thoughts with words.

Conceptual challenges also face those who embrace the three intuitions, raising doubts about the possibility that human cognition could differ fundamentally from nonhuman cognition, change qualitatively over development, or depend on language. The evolution of humans was a recent event, and evolutionary change works by modifying existing structures, not by creating new ones from whole cloth. How, then, could humans have evolved wholly new ways of thinking? Learning plays a large role in the development of human knowledge, and it is constrained by the learner's preexisting representational capacities. How, then, could children's conceptions undergo radical change? One can only come to understand the words and expressions of a specific language if one can relate each word or expression to preexisting conceptual representations. How, then, could language learning result in an increase in the learner's conceptual resources?

Despite the evidence and arguments to the contrary, I suggest that there is something right about all three of the initial intuitions: human cognition does have unique properties, those properties emerge over the course of human development, and they relate to the acquisition of language. In this chapter, I defend these intuitions by presenting a case study in comparative, developmental cognitive science. The case lies in the domain of spatial memory and concerns the process by which one reorients oneself after losing one's sense of position and heading. We will see that human reorientation depends in part on processes that are homologous to those in other animals, constant over much of human development, and independent of language—just as those skeptical of the three intuitions would expect. Nevertheless, human navigation also depends on spatial representations that are unique to humans, emergent over development, and related to the acquisition of a specific natural language. The case study provides a perspective on the development of thought and language that may meet the conceptual challenges facing the three intuitions. In closing, I suggest other aspects of human cognition that might usefully be approached from the same perspective.

Comparative Studies of Reorientation

Mobile animals who return to fixed places within the environment have mechanisms for representing their changing position in relation to those places. One set of mechanisms, found in animals from ants to humans, accomplishes this task through a process of "dead reckoning" or "path integration": a moving animal continuously updates a representation of its position relative to its starting point by combining information about its position at the start of the updating step and its velocity over that step. Dead reckoning is subject to cumulative errors, however, and animals from ants to humans have mechanisms for correcting them. When an animal finds itself in a familiar environment, it draws on its memory for the positions and directions of features of that environment to correct errors in its current reckoned position and heading. My case study focuses on this process of error correction, or reorientation.

Because reorientation requires some form of spatial memory, comparative cognitive scientists can investigate the nature of the information that enters this representation and the processes that operate upon it. Cheng and Gallistel (Cheng, 1986; Margules and Gallistel, 1988) studied reorientation in rats in a rectangular chamber with a rich array of visual and olfactory landmarks. Hungry rats were shown the location of partially buried food, they were taken from the environment and disoriented, and then they were returned to the environment and allowed to search for the food. To the investigators' surprise, rats searched the two geometrically appropriate locations within the room with equal frequency, despite the fact that the locations bore different relations to the nongeometric features of the environment (Figure 15.1). This search pattern was obtained only when rats were disoriented; rats readily used nongeometric landmarks in other spatial memory tasks.

Cheng and Gallistel concluded that rats reorient by comparing the shape of their current surroundings to a geocentric representation of the shape of the environment they had previously encountered when oriented. Because this comparison is task-specific (it is invoked only for purposes of reorientation) and informationally encapsulated (it operates only on information about the shape of the environment), Cheng and Gallistel concluded that reorientation in rats is accomplished by a "geometric module." Although their claim for modularity is controversial, research from other laboratories has confirmed Cheng and Gallistel's central findings of a task-specific reliance on geometric information (Biegler and Morris, 1993; Dudchenko et al., 1997).

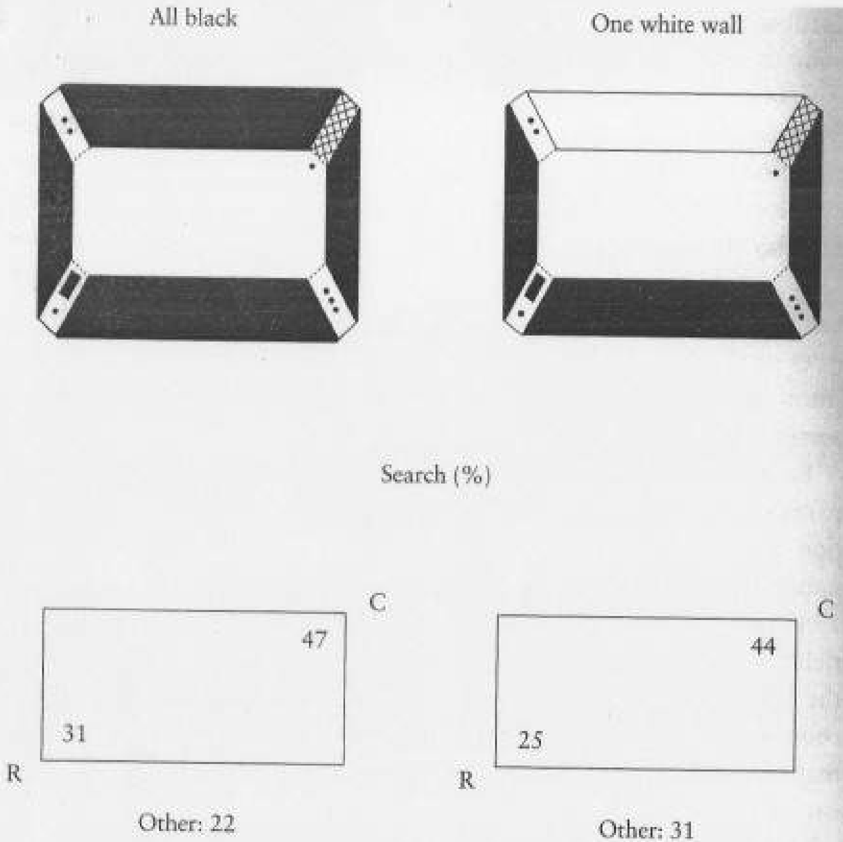

Figure 15.1. Testing environments and search patterns in two studies of reorientation and spatial memory in rats (Cheng, 1986). Rats searched at high levels at both geometrically appropriate corners of each chamber. Although they appeared to search the corner with appropriate nongeometric properties more than the opposite corner, this tendency was not significant (Cheng, 1986) and may be an artifact of incomplete disorientation (Margules and Gallistel, 1988).

The "Geometric Module" in Humans

Do humans have a homologous reorientation mechanism? Linda Hermer-Vazquez, Ranxiao Frances Wang, and I attempted to answer this question by adapting Cheng and Gallistel's experiments for young children (Hermer and Spelke, 1994, 1996; Wang, Hermer-Vazquez and Spelke, 1999). In our studies, 1.5- to 2-year-old children were brought individually into an experimental chamber by a parent, who hid a toy in one of the chamber's corners. Then the children were lifted and turned slowly with their eyes covered to induce a state of

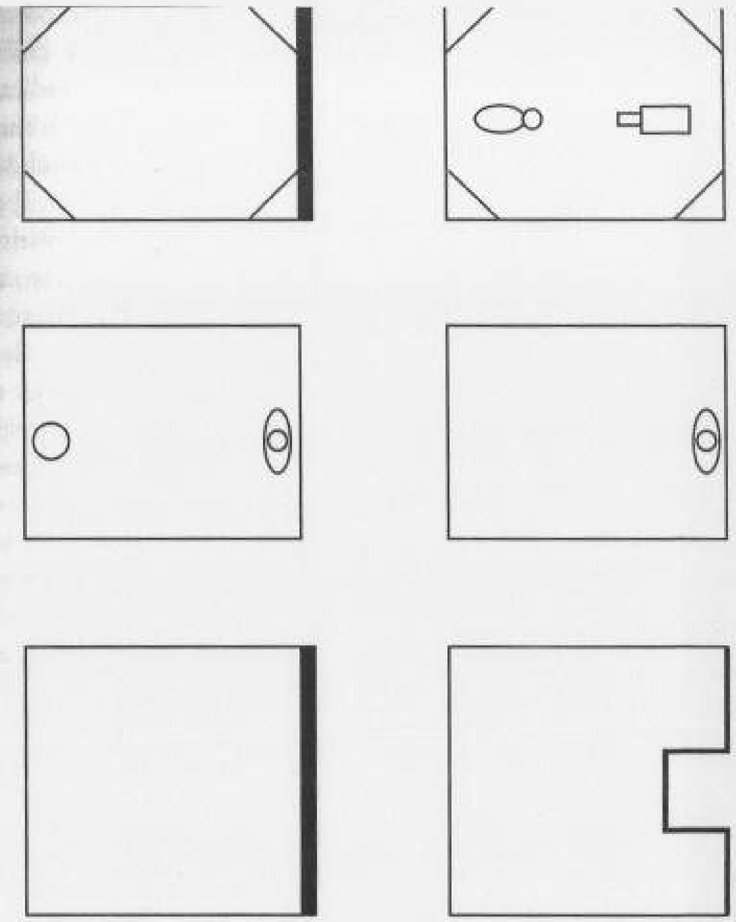

Figure 15.2. Testing environments used in studies of reorientation and spatial memory in young children (Hermer and Spelke, 1994, 1996; Wang, Hermer-Vazquez, and Spelke, 1999). Children searched with high and equal frequency at the two geometrically appropriate corners of the rectangular chamber, the four corners of the square chamber, and the single correct corner of the square chamber with the protuberance. The children's search did not accord with the colors of walls, or the presence or identities of movable objects.

disorientation (but not dizziness). Finally, they were released in a standing position facing one of the walls of the chamber, their eyes were uncovered, and they were encouraged to find the toy. In different experiments and conditions, we varied the properties of the chamber so as to determine the information children used to guide their search for the object (Figure 15.2).

In one condition, children were tested in a rectangular room with entirely white walls and no distinctive landmarks. These children searched the two geometrically appropriate corners equally, indicating that they were truly disoriented and that no inadvertent cues in the environment served to guide them to the object. Moreover, the children searched those two corners markedly more than the other two, geometrically inappropriate corners, indicating that they were sensitive to the geometric information used by rats. In a second condition, children were tested in the same room with a single, distinctively colored wall. Like rats, children continued to search the two geometrically appropriate corners with high and equal frequency, indicating that they failed to use the colored wall to relocate the object. In further experiments, we presented distinctive toys as symmetry-breaking landmarks, drew children's attention to the landmarks in various ways, allowed children to play in the chamber for several hours so that nongeometric landmarks became highly familiar, and reduced the informativeness of room geometry by testing children in a square or circular environment (Wang, Hermer-Vazquez, and Spelke, 1999; Gouteux and Spelke, 2001; see also Stedron, Munakata, and O'Reilly, 2000). None of these manipulations affected the findings: like rats, children searched for the hidden toy in correct relation to the shape of the room and without regard for the room's nongeometric landmarks.[1]

Was the children's search guided by a task-specific mechanism for reorientation? To investigate whether children truly reoriented by the shape of the room, Hermer-Vazquez (Hermer, 1997) investigated disoriented children's search for multiple landmarks (two hidden toys and the concealed chamber door) in a rectangular room with a single blue wall. When asked to point to each hidden object and to the door, children pointed with high and equal frequency to the correct location and to the geometrically equivalent, opposite location: once again, their search was guided by the shape of the room and not by the nongeometric landmark. Most important, however, children who pointed at the correct location for one of the objects pointed correctly for all of them, whereas children who pointed to the opposite location for one object showed the same reversal for the others. These findings provide evidence that children did not use local properties of the shape of the room to specify directly the individual locations of the objects. Instead, children evidently used the shape of the room to reorient themselves and, once oriented, searched for the objects in their remembered locations. Like rats, disoriented children locate objects in a familiar environment through a two-step process, in which they first reestablish their own geocentric orientation and then move to the remembered, geocentric positions of the objects.

Further experiments investigated whether children's reliance on room geometry stems from the "informational encapsulation" of the reorientation mechanism or from a more general, task-independent property of children's spatial memory. In a series of studies (Hermer and Spelke, 1996; see also Wang, Hermer-Vazquez, and Spelke, 1999), we compared children's search for a toy hidden in a corner of a rectangular environment under two sorts of conditions: in one condition, the toy remained in an apparently stable position and children were disoriented. In the other condition, the child remained oriented, with eyes closed, while the hiding places in the room were moved. Even when children viewed exactly the same environment in these two conditions, their search patterns were different: oriented children's search was guided by the nongeometric properties of the hidden object's container, but disoriented children's search was guided by the shape of the room (Figure 15.3). Search guided by geometry therefore appears to be specific to the task of reorientation. Like rats, children have a task-specific, encapsulated system for reorientation.

All these findings provide evidence for a close homology between the spatial representations and navigation processes of humans and rats: contrary to the first intuition with which I began, human navigation so far does not appear to depend on cognitive processes unique to humans. The plot thickens, however, when we turn from young children to older children and adults.

Developmental Changes in Spatial Representations

Adults were given the same reorientation task as young children in some of the same environments (Hermer and Spelke, 1994). When they were tested in a rectangular room with no distinctive landmarks, adults performed like young children and rats, searching the two geometrically correct locations with high and equal frequency. This find-

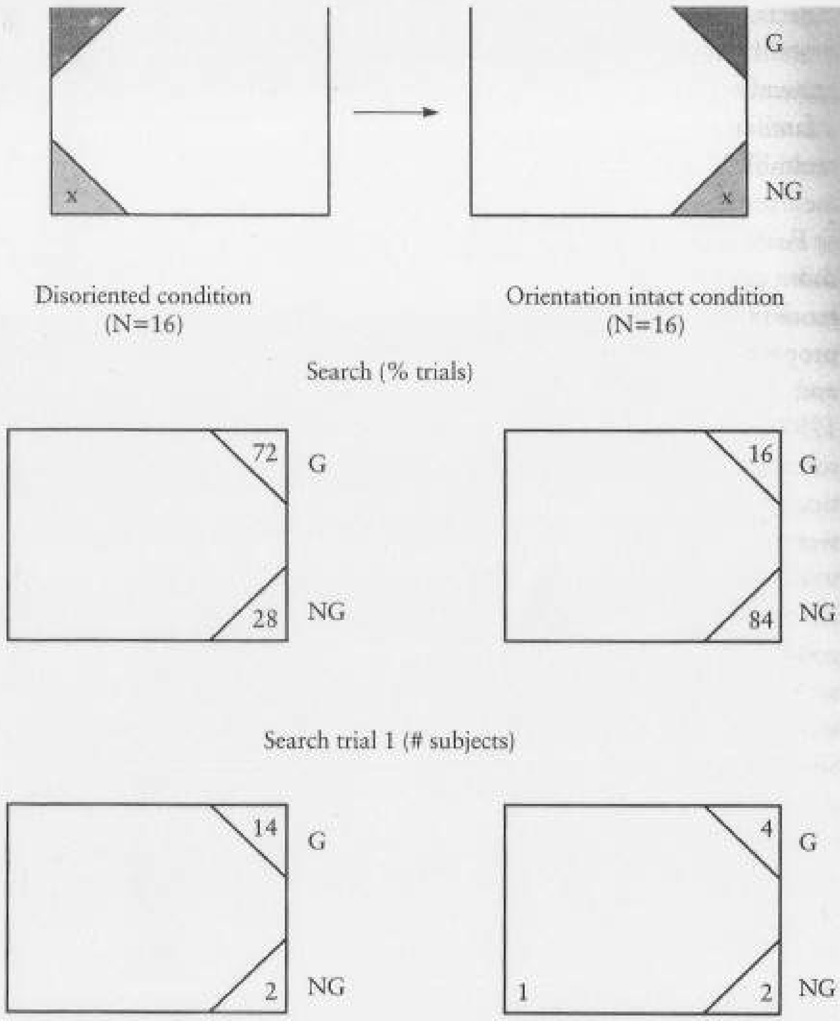

Figure 15.3. Testing environment and search patterns in a study of reorientation and object search by young children (Hermer and Spelke, 1996). For all children, an object was hidden in one of two distinctly colored and patterned boxes in adjacent corners, children's eyes were covered, and the boxes were moved to new locations that dissociated their geometric and nongeometric properties. Children who remained oriented during the boxes' displacement searched the box with the appropriate color and patterning, whereas those who were disoriented did not. Different search patterns were observed even on the first trial, before the children could know whether their task would be to locate a displaced object or to reorient themselves. Children evidently perceived and remembered both geometric and nongeometric properties of the hiding locations and used different properties selectively in different tasks.

ing suggests that the geometric reorientation system found in rats and children is present and functional in adults, a suggestion supported by new research using functional brain imaging (Epstein and Kanwisher, 1998). When a nongeometric landmark (a blue wall) was present in the rectangular environment, in contrast, adults outperformed young children and rats and confined their search to the single, correct corner of the environment. Sometime between two and twenty years of age, humans evidently come to locate objects under circumstances that defeat adult rats.

Further studies by Hermer-Vazquez, Moffet, and Munkholm (2001) investigated the development of this ability by testing children of various ages in the same environment. Children began to perform like adults, confining their search to the single correct location, at about six years of age. Those who succeeded at the task, moreover, often used spatial language to comment on their success.

To focus more directly on the transition from reorientation by pure geometry to the use of nongeometric landmarks, Hermer-Vazquez, Moffet, and Munkholm (2001) conducted a further study of six-year-old children, asking what other cognitive changes accompany the transition. In one session, children were given the reorientation task. In that session and a second session, a different investigator gave the children a battery of tests of spatial and verbal working memory, IQ, vocabulary size, comprehension of spatial expressions using the terms "above," "below," "front," "back," "left," and "right," and production of spatial expressions using the same terms. About half the children were found to reorient as adults do, using a colored wall to break the room's symmetry and specify the object's location. Stepwise regressions, with chronological age, sex, and performance on each of the other tests as predictor variables, revealed that the only factor associated with success on the reorientation task was performance on the language production task with expressions involving "left" and "right." Successful use of the nongeometric landmark was associated with successful production of spatial language.

These studies suggest that humans form spatial representations not found in other animals, and that these representations emerge over the course of human development. Do the representations depend on language? For familiar reasons, correlational research cannot answer this causal question, and so our last studies have taken a different approach. If uniquely human patterns of navigation depend on human language, then those patterns should disappear in any situation that prevents the normal exercise of the language faculty. We have tested this prediction in studies with normal human adults, using a dual-task method (Hermer-Vazquez, Spelke, and Katsnelson, 1999).

Turning Humans into Rats: Dual-task Studies

In these studies, disoriented adults again searched for an object hidden in a square or rectangular environment with a single distinctively colored wall. In one condition, subjects searched with no interference, as in our previous studies. In a second condition, subjects engaged in a simultaneous task of verbal shadowing: throughout the reorientation test, they listened to and repeated a continuous prose passage. This demanding task was designed to occupy the language faculty throughout the study and to prevent adults from using language to encode properties of the environment. Unfortunately, verbal shadowing is also quite demanding of attention and working memory, and so a further condition was included in the experiments. In that condition, subjects engaged in a nonverbal, rhythm-shadowing task: throughout the reorientation test, they listened to a changing succession of rhythmic drumbeats and continuously reproduced the rhythms by clapping. In a separate experiment, the verbal and rhythm-shadowing tasks each were performed with the same output system, concurrently with an attention-demanding visual search task. As judged from performance on the visual search task, the rhythm-shadowing task was at least as demanding of attention and effort as verbal shadowing. Unlike verbal shadowing, however, rhythm shadowing placed no demands on the language faculty.

The findings of our experiments are simply summarized: adults who engaged in rhythmic shadowing performed like adults in our original studies and searched in the correct relation to the nongeometric landmark. In contrast, adults who engaged in verbal shadowing performed like young children and rats and searched equally in the two geometrically appropriate locations (Figure 15.4). Geometrically appropriate search was as high as it is for children and rats in both shadowing

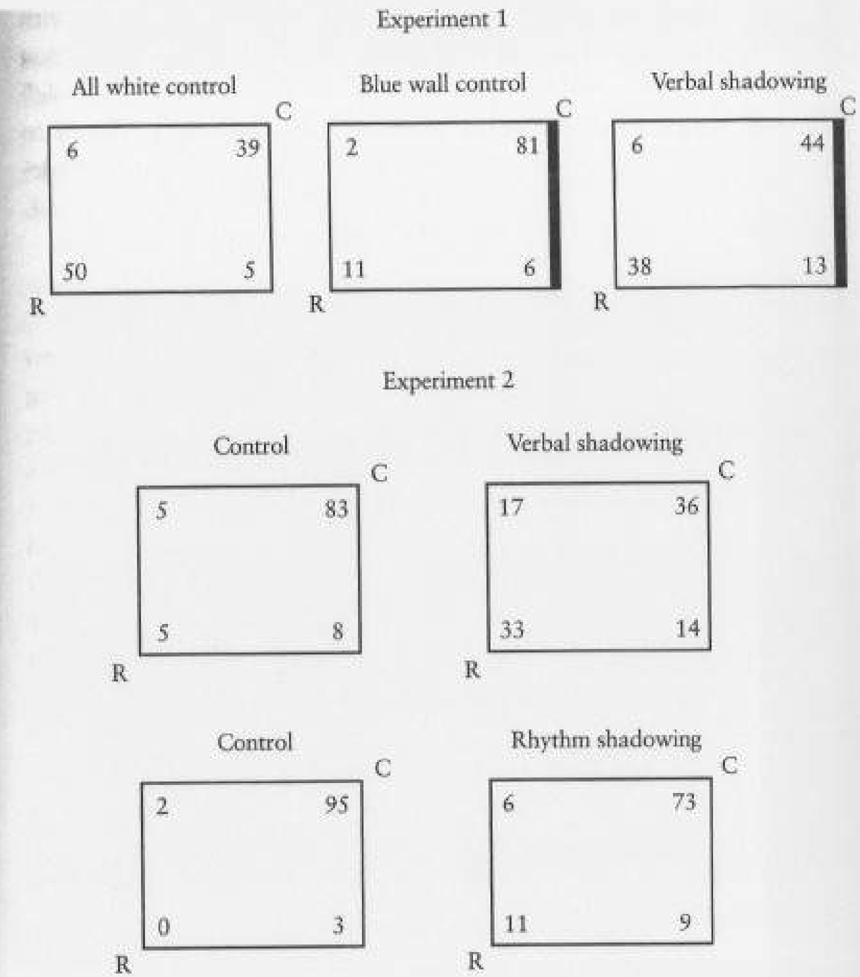

Figure 15.4. Testing environment and search patterns in a study of reorientation and spatial memory in adults (Hermer-Vazquez, Spelke, and Katsnelson, 1999). Adults searched in accord with both geometric and nongeometric information when they searched without distraction or performed a nonverbal distractor task. When engaged in a verbal distractor task, in contrast, adults searched in accord with geometric information alone.

conditions, suggesting that verbal shadowing did not interfere with memory for the object's location or with the geometric reorientation process. This finding provides evidence that Cheng's "geometric module" is alive and functioning in human adults. In contrast, adults' ability to search in the correct relation to the nongeometric landmark evidently depended on the use of language, for it was abolished by verbal shadowing.

Core Systems and New Combinations

This case study provides evidence both for and against the three intuitions with which we began. Contrary to claims that human thinking is unique, emergent over development, and dependent on language, we have found evidence for a system of representation—Cheng's "geometric module"—that is shared by humans and rats, constant over development, and impervious to verbal interference. This system allows both children and adults to reorient themselves and locate hidden objects. In accord with the initial intuitions, however, we have found evidence for a further system of representation that has not been observed in rats or other animals, that emerges over human development, whose emergence coincides in time with the acquisition of spatial language, and whose functioning is suppressed by verbal interference. What is the nature of the latter system, and in what ways might it depend on language?

To approach these questions, consider first what the language-dependent system does *not* do. Humans do not need language in order to notice, remember, or act on nongeometric information, because both infants and rats have all these abilities. Humans also do not need language in order to notice, remember, or act on the sense relationships encoded in language by the terms "left" and "right." Both Cheng's rats and Hermer-Vazquez's toddlers showed high sensitivity to sense relationships, for only those relationships distinguished the geometrically appropriate corners of the rectangular room (for example, the corners with a long wall on the *left*) from the inappropriate corners (those with a long wall on the *right*). Colors, patterns, lengths, and sense relations are all detectable and memorable independently of language, and all serve to guide the actions of nonverbal animals and preverbal children.

What rats and young children appear not to do is to combine these sources of information flexibly. Although rats and children represent the sense relations among walls of different *lengths,* they do not appear to represent the sense relations among walls of different *colors. Left, blue,* and *wall* are concepts available to the rat and the young child, but *left of the blue wall* is not.

This small example raises a larger possibility. Humans and other animals may share a common collection of innate, domain-specific cognitive systems, each of which gives rise to a set of core concepts. Distinctively human, developmentally emergent cognitive achievements may stem in part from our unique ability to form new combinations of these concepts, and that ability in turn may depend on the acquisition of a natural language.

How can a natural language be learned in the first place, if the concepts it expresses are not yet available to the child? Children may learn the words and expressions of a natural language by drawing on the concepts that their core, language-independent systems of representation make available. For example, the term "left" could be learned by relating the language-independent spatial representations used for navigation or object localization to expressions such as "turn left" or "look on the left." Terms for nongeometric landmarks and their properties could be learned by relating language-independent representations of objects or scenes to expressions such as "the blue box" or "the blue sky."

Once these terms are learned, natural languages may make new representations available, because of two of their most remarkable properties. First, a natural language is a combinatorial system: once terms have been learned in the context of one set of expressions, they can be used and understood in other sets of expressions with no further learning. Second, a natural language is a domain-general system of representation: its combinatorial rules concatenate entities only in accord with the syntactic properties of those entities and irrespective of their domain-specific content. Although nonverbal animals and preverbal children also have combinatorial representational systems, those systems operate in restricted domains. The present case study, for example, concerns a language-independent system that combines sense and distance relations (allowing rats and preverbal children to represent corners with a *short* wall on the *left*) but not sense and color relations. A speaker of English, in contrast, can combine sense relations not only with geometric properties but with nongeometric properties such as color ("the corner with the blue wall on the left"), number ("left of the first seven houses"), arbitrary associations ("left of the tunnel where Diana died"), or any other properties we have words to express.

The explosive, domain-independent combinatorial power of natural language may give human thinking its unique flexibility, and the acquisition of a natural language may underlie the emergence of new concepts and conceptual resources in children. Nevertheless, language is too powerful a combinatorial system, for it allows speakers to form bizarre and senseless combinations as well as useful and meaningful ones. Because nothing in the language faculty serves to distinguish potentially significant combinations from senseless ones, other selective processes are needed to guide children and adults toward useful combinations. Instruction, observation, and trial-and-error learning all may play this role (see Chapter 23).

Surveying the Landscape

These sweeping claims are a heavy burden for a small case study to bear; might they apply in other domains? Research on children's developing concepts of objects, of persons and their actions, and of number suggests other cases where uniquely human thinking may emerge through the acquisition of language. I sketch each case briefly.

Objects

Human infants and other primates have elaborate, and similar, abilities to perceive and represent objects. Young children nevertheless take a major step beyond the smartest nonhuman primates when they begin to learn about artifacts. On a single exposure, toddlers who view an adult using a tool develop new and enduring knowledge about the functional properties of that object. Human knowledge about objects comes to include a complex mix of information about an object's composition, parts, affordances, history, and culturally sanctioned functions. The ability to combine diverse sources of information into unitary object representations may be one source of the distinctively human propensity to surround ourselves with things of our own making.

What accounts for this ability? Human infants and nonhuman primates may be sensitive to many of the kinds of information that enter into mature representations of artifacts. Only verbal children and adults may combine these representations, however, so as to form concepts of objects with both physical properties and conventional functions, and natural language may provide the medium in which this combination of information is represented. The first steps of this process may occur when children learn their first words for kinds of objects (see Xu and Carey, 1996, for evidence and discussion).

Human Action

A wealth of research over the last two decades has investigated the emergence, in ontogeny and phylogeny, of a "theory of mind": a distinctive way of viewing, predicting, and explaining the actions of people and other animals as guided by their intentions, tempered by their emotions, and planned in accord with their perceptions and representations of their surroundings. Although early observations suggested that this intentional view might be common to humans and other primates (Premack and Woodruff, 1978; Whiten and Byrne, 1988), subsequent studies have provided very limited evidence for theory of mind reasoning in any nonhuman primate (Premack, 1988; Cheney and Seyfarth, 1990; Povinelli and Eddy, 1996; compare Hare et al., 2000). Similar research with children provides evidence for marked developmental changes in reasoning about human action. Very young children appear to represent human actions as directed to goals (Gergely et al., 1995; Woodward, 1998), as responsive to events perceived at a distance (Spelke, Phillips, and Woodward, 1995; Hood, Willen, and Driver, 1998), and as guided by desires (Wellman, 1990). In contrast, two-year-old children fail to reason about actions as guided by states of knowledge, and three-year-old children consistently fail to predict a person's actions from knowledge of her beliefs when the beliefs are false (for example, Perner, 1991). These findings suggest that an understanding of actions as guided by mental states develops slowly over the preschool years.

If "theory of mind" reasoning is distinctively human and emergent over development, what are its origins? The research described above suggests that young children understand desires and thoughts as directed to simple objects and actions. For example, young children can represent a given individual as *wanting an apple, wanting to jump,* or *thinking about Fred.* These language-independent representations may allow children to learn the meanings of verbs such as "want" and "think" when they appear in corresponding expressions. Studies of young children's spontaneous use of the verbs "want" and "think" are consistent with this possibility (Bartsch and Wellman, 1997). Further language-independent representations of states of affairs (for example, *Fred is late* or *John cut the apple*) would allow children to learn simple expressions describing those states of affairs. Once children have learned these expressions, the syntactic rules of their language allow for the construction of more complex expressions with embedded complements: for example, "I want John to cut the apple," "I think Fred is late." The syntax of embedding may provide the combinatorial machinery needed to represent propositional attitudes, which in turn may allow for the development of a theory of mind.

Recent research by de Villiers and de Villiers (1999) is consistent with this hypothesis. Their studies of normal and language-delayed children provide evidence that the emergence of the ability to express and understand sentences with embedded complements—sentences such as "John said that it's raining" or "Mary thinks we're crazy"—precedes and predicts success on false belief tasks. The acquisition of a natural language therefore might play a role in the development of an understanding of false beliefs and other propositional attitudes.

Number

Although many have proposed that knowledge of number is dependent on language, this claim remains problematic (see Chomsky, 1986; Bloom, 1994; Gallistel and Gelman, 1992; Dehaene, 1997). How could language be the source of our "number sense"? If it were, then how could knowledge of counting and arithmetic ever develop in children? Could abstract properties of the language faculty (recursion, discrete infinity) be harnessed for other domains?

A view of human cognition as founded on core systems, linked by language to form new combinations, suggests an approach to these questions (Spelke and Tsivkin, 2001). A language-independent number sense may arise from core systems for representing discrete, small numbers of objects and for representing approximate quantities: systems found in human infants and other animals (Dehaene, 1997; Scholl and Leslie, 1999). Children may learn the meanings of the first words in the counting sequence by mapping the words both to object representations (for example, "two apples" refers to *an apple and another apple*) and to magnitude representations (for example, "two apples" refers to *a very small quantity of apples* or *the next-to-smallest quantity of apples*). Because all the counting words follow a single sequence, children who have learned the meanings of "one," "two," and "three" may come to realize that each word in the sequence denotes both a distinct, discrete set of entities and a distinct magnitude (Wynn, 1992). Number words, on this view, serve as links for combining representations that exist independently of language but that have no privileged relation to one another.

This view predicts that mature representations of large, exact numerical magnitudes will show language dependence, whereas mature representations of small sets and of approximate numerical magnitudes will not. Studies of bilingual arithmetic and of numerical processing in language-impaired neurological patients provide some support for these predictions (Dehaene, 1997; O'Kane and Spelke, 2001; Spelke and Tsivkin, 2001).

Languages of the Brain

My case study in comparative, developmental cognitive science suggests a set of tasks for cognitive neuroscientists. We need, first, to chart the homologies between human and nonhuman cognition: to find and decipher the languages of the brain that are common to humans and other primates, and even to more distant animals. There are likely to be many such languages, in my view, embodied in distinct brain systems. If that hunch is correct, then cognitive neuroscientists can use the increasing array of tools at our disposal to study these systems at multiple levels and in multiple species.

The task of cognitive neuroscience will not end, however, with the charting of these homologous systems, for we need also to explore the distinctive ways in which humans combine their systems to form new concepts and new solutions to problems. I am speculating that each monolingual person may have just one language of the brain for combining expressions for his or her diverse mental languages. When humans solve problems that only we can solve, or think thoughts that only we can entertain, the multiple languages of the brain may communicate with one another by means of a single language that we also use to communicate our thoughts to one another. Discovering how this internal communication takes place in the fluent adult, and how it emerges in the developing child, could challenge cognitive neuroscientists for some time.

Note

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1. Young children do reorient by a nongeometric landmark, such as a wall of a distinctive color, when they are tested in a much larger environment such that the landmark appears at a considerable distance (Learmonth, Newcombe, and Huttenlocher, in press). Room size appears to be the critical variable, for such children fail to reorient by the same nongeometric landmark when tested in an otherwise identical environment of the size of the room used by Hermer and Spelke (Learmonth and Nadel, personal communication, 2000). In a large room, it is possible that a distant, asymmetrically placed surface that contrasts with its surroundings in brightness will serve as a compass signal for humans and for other animals (Mittelstedt, personal communication, 1996; Wang and Spelke, 2000).

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