Investigations in the development of spatial reasoning:

Core knowledge and adult competence

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Fodor’s modularity thesis (1983) breathed new life into the idea that the faculties of the mind might be compartmentalized in some interesting way. Drawing upon Chomsky’s arguments postulating an innate organ for language acquisition, Fodor suggested that the brain might entail several such “organs” to deal with various types of information, and he dubbed them modules. He famously guessed that these modules would likely be innate, domain-specific, informationally encapsulated, and automatically activated given the proper input.

The implied consequences of this position for development are articulated by Fodor in *The Modularity of Mind*. Infants have modules; preschoolers have modules; adults have modules; these modules do not change radically over the course of development. Since this proposal, people have posited a variety of modifications to Fodor’s version of the modularity thesis. Some have suggested that modules are a sensible idea, but that they emerge over development rather than starting out as an innate endowment (e.g., Karmiloff-Smith, 1992). Others have posited that innate modules are a sensible idea, but that they operate primarily in infancy and yield to more flexible, non-modular cognition in adulthood (e.g., Gauthier et al., 2000). While all of these stories may be true for different cases, the question remains: what is the status of modules over the course of development?

In this chapter, we argue that something like modules exists in infants and that adult cognition is built out of infant knowledge but also qualitatively different from infant knowledge. This argument has previously been made for various aspects of cognition, including knowledge of the physical world (Carey & Spelke, 1994; Spelke, 2000) and knowledge of number (Spelke & Tsivkin, 2001). Here we focus on the domain of spatial cognition, specifically the case of spatial reorientation (Cheng, 1986; Margules & Gallistel, 1988). As for object and number
concepts, empirical evidence supports the idea that some important elements of spatial cognition are available to infants and young children. Furthermore, the spatial reasoning behaviors of adults remarkably supercede those of children, revealing a developmental gap that requires explanation. Here we present evidence that language provides a mechanism for children to cross this gap. This research is in line with previous empirical work on the role of language in the development of number concepts (Spelke & Tsivkin, 2001) and theory of mind (de Villiers and de Villiers, 2003), as well as theoretical work on philosophy of mind (Carruthers, this volume).

The specific hypothesis that language learning supports the development of spatial cognition has been spelled out previously (Spelke, 2003), and the research presented here represents a first attempt at testing the validity of this position and elucidating the mechanism by which language might play a role.

1. Core knowledge and adult competence: a brief review

The core knowledge hypothesis holds that certain kinds of concepts – for example, concepts of number, space, and objects – are available even to very young infants (Spelke & Newport, 1998; Spelke, 2000). Core knowledge is related to adult knowledge in that knowledge structures present in infancy compose the building blocks of adult cognition. In early versions of this theory, systems of core knowledge were suggested to be uniquely human and early-emerging. Over time, research has suggested that core knowledge is early-emerging but not uniquely human (Spelke, 2003). Under the revised conception, core knowledge is supposed to be innate because it is, by definition, the kind of knowledge that we share with other animals, and is therefore presumed to be genetically specified and guided by evolution more than by individual experience. The empirical implications of the core knowledge proposal are that certain kinds of
knowledge will be evident both across development, from infancy through adulthood, and across species, from humans to rats and maybe even ants.

The core knowledge hypothesis shares many features with the modularity hypothesis. Core knowledge, like modular cognition, is divided into domains (number, objects, space); core knowledge is innate; core knowledge implies automatic and task-specific processing. It is important to keep in mind, however, that the two claims are independent; core knowledge is fundamentally a claim about ontogeny, whereas the modularity thesis is a claim about information processing. Nevertheless, it may be turn out to be true that core knowledge systems are, in fact, modular in pretty much the way that Fodor described. If this is the case, then statements about what happens to core knowledge over the course of development can be viewed as claims about modularity over the course of development. In this chapter, we will refer to core knowledge, but with the idea in mind that whatever conclusions we draw may cash out as claims about what happens to modules over the human lifespan.

Evidence for the core knowledge position comes from many lines of research (for a review, see Spelke, 2003). For example, there appears to be a distinct cognitive system for representing large approximate numerosities in infants (Xu and Spelke, 2000), adults (e.g., Barth, 2003; Dehaene et al., 1999), and animals (Hauser et al, in press). The rules that govern the operation of this system are consistent across development and across species. For instance, the large number discriminations of animals, infants, and adults are mediated by the ratio difference between the numbers, such that the larger the ratio between two quantities, the more discriminable they are. (Consider 42 and 87, a highly discriminable pair, versus 82 and 87, a practically indiscriminable pair.)
This is but one small example from the domain of number; similar stories have been told about a variety of knowledge domains such as goal-directed action, object mechanics, and space. Critically, in all of these domains, adult competence exceeds the behavioral limits granted by core knowledge. In the case of the approximate large number system, infants and animals do not show a capacity to think beyond the given ratio limits. Human adults, by contrast, can distinguish 82 from 87 – simply by counting.

If infants have some conceptual resources, but adults have dramatically more, three questions arise: 1) What are the innate conceptual resources available to human infants and children? 2) What happens to innate knowledge structures over development? 3) What are the mechanisms supporting transitions from the isolated systems of core knowledge to more flexible cognition?

Here we will focus on one possible answer to the second and third questions. Our proposal is that the domains of core knowledge, which start out independent and autonomous, gain the ability to interact with each other. 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, such as “I think he wants the cup that’s to the left of the newspaper.”

In particular, we will focus on how the combinatorial properties of language may facilitate a dramatic developmental transition in spatial reorientation ability. The goal of our review of the literature on spatial reorientation below is intended to make two points about this
partially worked case study: first, spatial reorientation bears hallmarks of core knowledge and of modularity, as well as adult competence that exceeds the initial abilities; second, language very likely plays a role in this developmental transition.

2. The case of spatial reorientation

While many navigating animals can represent their own changing locations by integrating information about position, direction, and speed, the mechanisms performing these computations are subject to cumulative errors. Therefore, animals need some sort of spatial representation in memory that can be used to correct errors, at least along familiar paths. This process of error correction, or reorientation, can be used to probe spatial representations in animals and humans through experiments which aspects of space animals and humans pay attention to when finding their way.

2.1 Comparative studies on reorientation

Previous studies of reorientation have demonstrated two fundamental points: that the reorientation abilities of animals and children are largely similar; and that the reorientation abilities of human adults dramatically exceed those of rats and children. In the earliest reorientation studies, food-deprived rats were shown the location of a food reward in 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 location and at the point located at a 180° rotation from the target, a location which had the same geometric relationship to the shape of the environment as the target location (Figure 1). Surprisingly, the rats did not use
any of the non-geometric cues, such as the distinctive odors, brightnesses, or textures in different regions of the environment, to distinguish between the two geometrically correct choices.

Figure 1. Mean search rates of rats in a reorientation task, expressed as percentage (%) of trials with first search at that corner. C: correct; R: rotated; N: near; F: far. Reprinted from Cheng, 1986.

A series of experiments by Biegler and Morris (1993) converged on a similar result. In their study, rats were trained to find a food reward in a square arena containing two landmarks with distinctive visual and olfactory features. For all of the rats, the relationship between a particular landmark and a food reward was preserved, so that the food reward was always, for example, 40 cm to the ‘south’ of a particular landmark. For one group of rats, the landmarks were in the same position on every trial; for the other group of rats, the landmarks were moved randomly on every trial. Only the rats in the stable landmark condition eventually learned to predict the location of the food. The rats in the moving landmark condition searched around the landmark associated with the food, but never learned to search in a location holding a particular relationship to a landmark, like 40 cm south of it. These results suggest that rats could use the geometric stability of the landmarks as a direct cue to the location of the food, but that they could not use the visual and olfactory properties of the landmark as an indirect cues. In both the disorientation paradigm of Cheng and Gallistel and in the landmark stability paradigm of Biegler and Morris, rats showed a remarkable imperviousness to the non-geometric features of the environment when searching for hidden food.
2.2 Reorientation in humans

A series of studies by Linda Hermer, Elizabeth Spelke, and Frances Wang (Hermer & Spelke, 1994, 1996; Wang, Hermer, and Spelke, 1999) demonstrated that children, like rats, reorient using the geometric features of the environment while ignoring salient non-geometric features during the task. Borrowing from the paradigm of Cheng and Gallistel, Hermer et al. tested 18- to 24-month-olds and adults 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 presence of the blue wall to search only in the correct corner. Children, however, performed like rats: they searched equally in both geometrically correct corners but failed to use the presence of the blue wall to restrict their search to the correct corner (Figure 2).

![Figure 2](image-url)  
Figure 2. Children’s mean search rates in a reorientation task with a) all white walls and b) one red wall. Rates are expressed as percentage (%) of trials with first search at that corner. C: correct; R: rotated; N: near; F: far. Reprinted from Hermer & Spelke, 1996.
A series of controls ensured that the failure lay specifically in using the non-geometric features to reorient. In one set of studies, children played games that made the colored wall highly salient. For example, the child would hear a xylophone play each time he hit the colored wall. Some children were brought in for multiple visits to make the colored wall especially familiar. Neither these nor several other manipulations increased the children’s use of the colored wall 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 and 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 non-geometric cues. The results from the rat studies have led Cheng to hypothesize the presence of a ‘geometric module’ in mammals (1986). According to Cheng’s proposal, the reorientation process is modular in the most
fundamental Fodorian sense of the word because in tasks requiring reorientation, only geometric information can influence the behavior, while other potentially useful information is simply not used at all. Human children seem to possess a similar ‘geometric module’ to the one that Cheng has proposed for rats. Adults, on the other hand, are not subject to these limitations. Instead, there appears to be a radical shift over the course of human development that promotes a nearly effortless ability to use non-geometric as well as geometric information to recover from disorientation.

2.3 Empirical challenges to the modularity argument in spatial reorientation

While an abundance of evidence suggests that geometry is a critical cue to many different animals engaged in navigation and reorientation, some recent empirical work has challenged both the notion of a ‘geometric module’ and the hypothesis that human language serves to overcome the encapsulated nature of this module. Learmonth, Newcombe, and Huttenlocher (2001) replicated the original finding with five-year-old children, concluding that they fail the reorientation task in a small room but demonstrated that the same children succeeded in a large room. Gouteux, Thinus-Blank, and Vauclair (2001) tested the reorientation capacities of rhesus monkeys and found that the monkeys could be trained to reorient using a large red wall, but not to a small red square on that wall.

Experiments testing reorientation in the context of escape tasks have yielded even more surprising data. Dudchenko and colleagues (1997) have replicated the basic finding that rats ignore non-geometric cues during appetitive reward tasks, but have demonstrated that rats will use visual, non-geometric cues to find a platform in a water maze, an aversive escape task. Recently, even members of the fish species *Xenotoca eiseni* rapidly learned to use a red wall as a
cue to find the door leading out of their isolation chamber (Sovrano, Bisazza, and Vallortigara, 2002). There is clearly a puzzle to be solved here. Despite the difficulty of reconciling these data with the notion of an encapsulated, task-specific geometric module, there are numerous documented situations in which geometric information is privileged above all other kinds of information and fails to be used in conjunction with other relevant cues. How can these disparate findings be explained?

One possibility is that there is an encapsulated, task-specific module but it has been misdefined as exclusively ‘geometric.’ For example, Learmonth et al.’s finding that five-year-old children solved the task in a large room but not in a small room suggests that the size of the non-geometric cue might matter. Gouteux et al.’s finding that rhesus monkeys could learn to reorient by a large red square on the wall but not by a small red square supports the notion that the size or distance of a non-geometric cue enters into this computation. Perhaps a large enough non-geometric cue is usable in conjunction with geometry for reorientation. However these findings as explained, it is clear that animals and young children do not exhibit the same measure of cognitive flexibility that human adults have, which we claim is a consequence of language. After all, a human adult can reorient using a small visual cue spontaneously and on the first try in a task that is sensitive to verbal interference effects.

Biegler and Morris’s experiments (1993; described in the introduction) demonstrate that the stability of landmarks, perhaps in addition to their geometry, plays a role in animals’ landmark-based navigation. Taken together, these findings suggest a reconceptualization of the so-called ‘geometric module’ as an encapsulated and task-specific mechanism that searches for cues like size, stability, and geometric configuration of environmental features – precisely those cues that are dependable for navigation. Indeed, many researchers have argued that each of these
cues has ecological validity for navigating animals (e.g., Hermer & Spelke, 1996; Learmonth et al., 2002). Hills and oak trees are likely to maintain their size and geometric configuration over time, while the positions of snow patches, colors of the leaves, and location of small rocks probably will not.

Modifying the description of the ‘geometric module’ in such a way certainly yields a fairly different picture of how and why geometry is privileged in reorientation. However, such a redefinition does not damage the notion that the reorientation process is modular, depending on task-specific, encapsulated information, nor the claim that language is important for allowing the contents of this module to interact with other conceptual domains. In fact, this type of domain-specific central module has been posited by theorists and researchers attempting to extend Fodorian modularity to conceptual processes (Fodor, 1983; see Carruthers, section 1.2, this volume).

Perhaps more mysterious than the effects of size and stability are the discrepancies between search tasks and escape tasks. If rats and fish can use visual cues in reorientation when they are looking for an exit instead of for a positive reward, language certainly cannot be involved. It is terribly unclear why animals would engage different cognitive mechanisms in an escape task than in reward tasks. While the argument above suggests that the ‘geometric module’ was initially too narrowly defined, perhaps the claim that this module has a specific role in reorientation tasks is too broad. There appear to be distinct kinds of reorientation tasks; it is an open question whether escape tasks engage an escape-specific reorientation mechanism in the same way that reward tasks engage some version of the geometric module. It should also be noted that all of the escape tasks reported to date allow animals to find the exit on their own and learn over a number of trials to find it faster. It is possible that this learning mechanism, in
conjunction with the different demands of an escape task, elicits behavior that is not based on encapsulated processes to the same extent as tasks where animals learn the location of their reward by watching the hiding event.

In sum, recent research strongly argues against any simple notion of a geometric module. Reorientation appears to be a complex process sensitive to a variety of factors such as cue size and task demand, in addition to geometry. Nevertheless, many aspects of reorientation across a number of species still bear the hallmarks of modular processing, including a task-specific reliance on geometry in all tasks and an encapsulated imperviousness to many kinds of sensory cues in reward tasks.

2.4 The language hypothesis in the development of spatial representations and reorientation

What factors underlie the drastic difference in reorientation behavior between children and adults? The studies outlined above 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 which unambiguously selects the correct location but requires the use of the non-geometric feature red. Likewise, in Biegler and Morris’ experiments, rats could encode an association between a landmark and food, and they could encode a specific, allocentric location for food in a stable environment, but they could never learn to encode a particular spatial relation between a landmark and a food reward. 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* or *north of Landmark X*.

Spelke has put forward a hypothesis to explain how children become able to combine two forms of knowledge, a representation of objects (landmarks) and an ability to reorient based on geometric knowledge. According to her hypothesis, language allows humans to combine conceptual domains of core knowledge. The geometric module is an example of this type of 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*, Spelke suggests that the geometric module is sensitive to sense relations 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*. However, she argues that without language, 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*.

### 2.5 Two lines of evidence that language is important for reorientation behavior

Two lines of evidence suggest that language indeed plays an important role in the developmental change in reorientation performance. First, the age at which children begin to use landmarks to do the reorientation tasks highly correlates with their accurate production of the words ‘left’ and ‘right’ (Hermer-Vasquez, Moffet, and Munkholm, 2001). This 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. By contrast, when adults are asked to shadow a rhythm instead of words, they succeed in using the colored wall to reorient (Hermer-Vasquez and Spelke, 1999; Figure 3). This result cannot be explained away by the relative difficulty of the shadowing tasks, since a set of parallel studies indicate that the rhythm shadowing condition was actually more difficult than verbal shadowing, not less.

![Figure 3. Adults’ mean search rates a) under normal conditions and b) while engaged in a concurrent verbal shadowing task. Rates are expressed as percentage (%) of trials with first search at that corner. C: correct; R: rotated; N: near; F: far. Reprinted from Hermer-Vasquez & Spelke 1999.](image)

While both of these pieces of evidence provide compelling arguments for the notion that language is deeply involved in the developmental change in spatial representation described here, neither one provides a direct, causal link between language acquisition and novel conceptual combination. The correlation between ‘left’ and ‘right’ production and reorientation performance is intriguing, but it could certainly be argued that the child’s spatial representations change first, enabling better reorientation performance, and that the spatial terms are acquired second. Put simply, correlation does not imply causation. Moreover, there is no intuitive reason
why language should precede conceptual change; it is just as likely that a purely non-linguistic 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 task with adults provides converging evidence that language is important, but there are several caveats that keep this from providing a knock-down argument that language acquisition precedes the change in spatial cognition. Adult cognitive systems are considerably different than those of 2-year-old children; thus, it is possible that spatial cognition is simply more intertwined with language in adults. Adults have years of practice sharing spatial concepts with each other through language; it might be logical to suspect that this extended practice promotes more verbalized spatial representations than those of children. After all, a large body of data in various domains suggests that habitual patterns of language use have cognitive consequences for non-linguistic tasks (e.g., Boroditsky and Schmidt, 2000). Alternatively, adults might use a completely different representational system for reorientation than children do, one which happens to depend on language; perhaps when this most-used system is compromised, adults revert to a less efficient backup system resembling the geometric module. There is no a priori reason to conclude that verbal interference breaks the bridge between the core systems. In short, it remains unclear exactly why verbal interference causes adults to reorient like children and rats.

In an attempt to address these alternative explanations for the apparent effects of language on reorientation, we embarked on a study that would provide more direct evidence for the hypothesis that language acquisition is causally related to a change in reorientation behavior. Specifically, we set out to find causal evidence showing that language acquisition both a) precedes and b) gives rise to the developmental change in spatial representation and behavior.
3. Does learning spatial language change reorientation behavior?

3.1 A training study: Motivation and design

In order to directly test the causal effect of language on reorientation, we decided to teach children the words ‘left’ and ‘right’ and see whether language learning would cause them to reorient like adults. 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 around 4½ 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 likely 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; 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 effect 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 and ever-present than either a hidden object or a red wall landmark. Therefore, we used a combined training procedure that attempted to first teach children to map the words left and right onto their own bodies and then to moveable objects placed at the children’s sides.
In designing the training as we did, we had several questions that we thought might get answered. First, we wanted to know whether training on left-right knowledge of any sort would have an effect on reorientation performance. Second, we wanted to know whether specific types of left-right knowledge might predict reorientation behavior better than others. Specifically, we were curious whether knowing how left and right apply to one’s own body parts would be a sufficient level of knowledge, or whether children would also need to know how these terms could be applied to external objects.

Our training procedure consisted of two comprehension games that followed an identical structure, the first focusing on body parts and the second focusing on objects. First, children were given a ‘body parts’ pre-test where they had to act out commands like “shake your left leg” or “tug on your right ear.” Following the pre-test, they continued to hear the same commands, but now they received feedback so that they could fix any errors and learn the correct use of the terms. Finally, they were given a post-test without feedback to assess how well they had learned these terms. The second game followed the same pre-test, feedback, post-test structure, but used commands like “show me the toy on your right” or “touch the toy on your left.” During all parts of the training, children stood in the center of the room and were continually asked to face different walls so that they would not learn the incorrect idea that ‘left’ and ‘right’ describe a particular spatial location in the room such as ‘by the door.’

Children came in for two sessions, typically a week apart. In the first session, children went through our language training procedure. In the second session, the post-test was re-administered to see whether children remembered what they had learned in the Session 1 training. They then walked to a separate room with a reorientation chamber and participated in up to eight trials of the reorientation task.
3.2 Methods

Participants.

Participants were 30 4-year-old children (mean age 4;4, range 3;10 to 5;9) recruited from Cambridge, MA and surrounding towns. 22 experimental subjects came in for two sessions, almost always a week apart. In the first session, subjects participated in the language training described below. In the second session, subjects repeated the post-tests from the two language games and then participated in up to 8 trials of a reorientation task. An additional 11 control subjects were tested only in the reorientation experiment and never participated in language training. All subjects were brought in by their parents and tested in our laboratory.

Language training.

The language training games were designed to be fun and to teach children the words ‘left’ and ‘right.’ Children were tested in a small room with several pieces of furniture and posters on the wall. We hung a sheet of distinctly colored poster board on the center of each wall.

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.” To make this fun, the game was described as a dancing game or an exercise game, and the child could choose which one he or she wanted to play. Distracter trials included neutral 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.” To make this more fun, the objects used were plastic vegetables, and the game was set up with an elaborate ritual of planting a vegetable garden all around the child. Distracter trials included trials asking for the object in front or back of the child, or referring to the color of the
object. The distracter trials ensured that all children could feel confident about getting some of the answers right and provided regular opportunities for hearty praise.

Both language games followed the same basic structure. The pre-test consisted of 16 trials, 8 trials using the words left or right interleaved with 8 trials of distracter instructions. Children faced each of the four walls for 4 trials. After the pre-test, children were told “Now we’re going to play the same game, but this time, if you make a mistake, we’ll correct it. That way you can learn what left and right means.” All children seemed to understand this explanation and agreed to proceed with the game. The training session consisted of the same set of commands used in the pre-test, but this time the children were given scripted feedback, either praise for correct answers or correction for incorrect answers of the form “No, that’s your left leg. Kick your right leg.” Every four trials, children were instructed to turn to face a different direction with instructions such as “Now let’s look at the red wall.” This was done in order to ensure that children were trained and tested facing a variety of directions; without this measure, children might learn that ‘left’ and ‘right’ referred to specific sides of the room as opposed to sides of their bodies. On each set of four trials, children received 3 left/right instructions and 1 distracter trial. The order of wall facing directions and instructions was randomized prior to the beginning of the experiment and all subjects received the same order. Training ended when the child answered correctly on 7 out of 8 consecutive trials or became too tired to continue.

The post-test was introduced with the following instructions: “Now we’re going to play the game one more time, but this time I am not going to correct you if you make a mistake. You have to try to answer all by yourself. You can do it – just do your best, OK?” A pilot study indicated that this instruction was necessary because, without it, many children took the absence of error correction in the post-test as tacit feedback that they had answered correctly. The post-
test was identical to the pre-test for the first 16 trials. In addition, 4 trials were added to the end consisting of novel instructions in order to assure that children’s learning generalized beyond the exact commands used in training. For the Body Parts game, the generalization commands were novel instructions such as “tug on your left ear.” For the Objects game, a new set of 4 toys was brought out to test generalization.

Reorientation.

For the reorientation task, we used a rectangular apparatus built according to the original specifications in Hermer & Spelke (1994). The dimensions of the room were about 4 feet by 6 feet. Three of the walls were covered with white felt fabric and one of the short walls was entirely covered with bright red felt fabric. The door was made of a loose flap of white felt that could be attached to the wooden frame with Velcro. When the door was closed it was indistinguishable from the other white walls. Blue fabric flaps in each of the four corners provided hiding places for the stickers.

Children were tested by the experimenter. 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 4-5 times. Before removing the blindfold, the child was asked to point to the door. A correct point indicated that the child was not fully disoriented, and the child was turned a few more times. The experimenter turned the child to face a particular wall and removed the blindfold, and the child was allowed to search for the sticker. The experimenter stood neutrally behind the child and looked up at the ceiling during this phase so as not to cue the child.

Children participated in up to 8 trials of this task. We used a block design such that children received 4 trials using one hiding place and 4 trials in a different hiding place. Children
faced a different wall of the room on each of the 4 trials within a block. The hiding places were counterbalanced across children with the following criteria. Some children saw the sticker hidden at the short red wall in the first block and at the short white wall in the second block, while others received the opposite order. Furthermore, the second block of trials always used a hiding place on the other diagonal of the rectangle than was used in the first block. The diagonals of the rectangle define its geometry, so the two corners that were geometrically appropriate in the first block became geometrically incorrect in the second block. This counterbalancing was not introduced until the experiment was already underway, so the experiment was not fully counterbalanced in this way. Additionally, not all children were willing to participate in a full set of 8 trials of reorientation (mean: 6.6 trials). Therefore, we explicitly tested for effects of wall color order and number of completed trials in our statistical analysis. Neither of these factors was responsible for the effects described below.

3.3 Results: Training on comprehension of right and left

Our first question was whether it would be possible at all to teach children the terms left and right. After all, many researchers including Piaget have commented on how late children learn these words (Piaget & Inhelder, 1948/1967). Of the 22 subjects who came in, three could apply the terms left and right to their own body parts at above-chance levels. None of those three subjects knew how the terms applied to objects placed at their left and right sides. The remaining children went through training on the Body Parts game, and 14 passed the post-test. Only one child spontaneously transferred her learning of left and right body parts to external objects, and 17 continued with training on the Objects game. 11 of these children made it all the way through the post-test, while children became too tired either during or after the feedback session to
complete the post-test. 6 of the 9 children completing the Objects post-test responded correctly at levels above chance.

While it seems intuitive from the Session 1 data that the children who passed the post-tests would be the same in Session 1 and Session 2, this is actually not the case. In fact, 4 of the 7 children who fussed out or failed during Objects feedback training in Session 1 passed the Objects Post-Test during their second visit. Apparently, the amount of feedback that they received during Session 1 was sufficient to spur their learning. These results suggest that the effects of training during Session 1 were somehow consolidated over the interval between visits, and that the true effects of training were best measured by the children’s performance on their second visit.

Of the original 22 subjects, 19 returned for a second visit and participated in a language assessment (simply a repetition of the post-tests). 11 children passed the Body Parts post-test, and 8 of these also passed the Objects post-test. In addition, 2 children passed only the Objects post-test. The learning data are summarized in Table 1. In short, about 40% of the children who participated in both training tasks in Session 1 demonstrated an improved comprehension of the terms left and right when they returned for a second visit.

<table>
<thead>
<tr>
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<th>Session 1</th>
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<th>Session 2</th>
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<tr>
<td></td>
<td>participating in training</td>
<td>participating in post-test</td>
<td>passing post-test</td>
<td>participating in check-up</td>
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<td>Body Parts</td>
<td>22</td>
<td>21</td>
<td>14</td>
<td>19</td>
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<td>Objects</td>
<td>18</td>
<td>11</td>
<td>6</td>
<td>17</td>
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<tr>
<td>Both games</td>
<td>18</td>
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Table 1. Numbers of subjects succeeding following training on two left-right tasks immediately after training (Session 1) and approximately 1 week later (Session 2). 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.

3.4 Effect of language training on reorientation

How did language training affect children’s behavior in the reorientation room? At first glance, neither knowledge of left-right on body parts nor knowledge of left-right on external objects, while often indicative of successful reorientation, seemed to tightly correspond with reorientation performance. However, a closer look suggested that success on both left-right language tasks did predict reorientation behavior. We therefore classified all of the subjects into one of two groups on the basis of their Session 2 language assessments. Learners were defined as children who were correct on 75% or more trials in both the Body Parts and Objects games during Session 2. Non-learners were defined as children who did not meet this criterion for both games. Eight children who participated in the reorientation task were classified as Learners, and nine were classified as Non-learners. All of these children had received some amount of Session 1 training, but the amount of training varied depending on the child’s stamina to get through the entire training procedure. As mentioned above, some of the children who had fussed out in Session 1 were classified as Learners based on their Session 2 performance, while other children who had made it happily all the way through Session 1 were classified as Non-Learners in Session 2. In other words, the length of time spent in training did not drive the difference between Learners and Non-Learners.

Consistent with the data from previous reorientation studies, both Learners and Non-Learners searched primarily in the two geometrically appropriate corners (p<.001). Learners, however, searched in the correct geometric corner significantly more often than non-learners.
We also compared the reorientation behavior of Learners and Non-Learners 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 Non-Learners and significantly below the performance of Learners \([t(16)=2.10, p<.05]\). Figure 4 shows mean search rates for Learners, Non-Learners, and untrained controls.

![Figure 4](image_url)

**Figure 4.** 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 classified as Learners refused to cooperate during the reorientation task, so the 7 remaining children contribute to this analysis.

**4. Discussion: Evaluating the current state of the hypothesis**

The results outlined above 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 are consistent with the claim that language acquisition plays a causal role in changing children’s reorientation behavior. Our findings 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, and further work in our lab is addressing this possibility.
Nevertheless, these data provide the strongest evidence to date that the acquisition of spatial language closely mirrors the development of reorientation abilities.

At the same time, these results leave open a number of questions. One fundamental question left unanswered is how exactly language relates to reorientation behavior. 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.” The possibility remains, however, that language learning enables a novel ability to reorient in some other way than what is proposed in this hypothesis, without combining information from isolated modules. In the remaining pages of this chapter, we consider some open questions regarding the effect of language on reorientation and some ways to begin divining the right explanation.

4.1 Is spatial language necessary and/or sufficient for developing adult reorientation?

The results of our study indicate that a certain amount of language learning is in fact sufficient to push children into adult-like reorientation. It bears asking exactly how much language learning is sufficient for this developmental step. Our data suggest that neither mapping the words left and right onto intrinsic body parts nor mapping the words to external objects is sufficient: Children need to understand both kinds of meaning for an observable benefit to reorientation skills. Perhaps there is an interaction between these two kinds of meanings that facilitates successful reorientation; or perhaps children, having gained both meanings independently, can infer a broader meaning of left that guides them in this task.

But is language learning necessary for successful reorientation? When language is knocked out through a verbal interference paradigm, adults’ search drops to chance levels. This
suggests that language is necessary for reorienting adults. A strong view that language is necessary would have to entail the notion that language uniquely solves this problem. A test of this hypotheses might come in the following form: Can children (or adults) be taught a strategy to correctly solve the reorientation task without language? If children could not learn a simple trick for remembering the location of the hidden sticker without language, a strong case could be made that language uniquely solves this problem. Conversely, if they could learn a non-linguistic mnemonic trick, it would be hard to insist that language is absolutely necessary for reorientation.

No matter what the outcome of such an experiment, the critical point about language is that it provides **cognitive flexibility**. Language learning, in one fell swoop, affords the ability to solve many tasks. Teaching children a mnemonic device for reorientation might help them succeed on reorientation, but it probably wouldn’t help them succeed on many other tasks. Teaching children left and right, however, is likely to help them succeed on a range of tasks they couldn’t do before. 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.

4.2 **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”? How does a child even begin to construct the meaning of this very abstract word?
Our data suggest ways to fine-tune the initial speculation that “left” maps onto output from the geometric module. Children map the words “left” and “right” onto body parts earlier and more easily than onto sensed spatial relations between objects. The results of the training study presented here, in which more children learned body-part meanings than object-related meanings of left and right, as well as data from our lab explicitly testing how willing children are to map particular meanings to these words (Shusterman & Spelke, unpublished data), suggest that “left” and “right” might not map directly onto the geometric module. So the narrative might be modified like this: children initially learn “left” and “right” as body part terms (left arm); then they map these terms onto sense relations (left of the short wall). It is this second meaning of “left” that can be combined with the output of other processing systems.

These findings make an important point. In order to understand just how language might combine distinct concepts, it is necessary to investigate how language maps onto each of the initial concepts. Without a well-informed guess about what is being combined by language, it is difficult to test whether language acquisition changes behavior by combining concepts or in some other way. We suggest that training studies, such as the one presented here, serve as a powerful tool to address this question. 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 pre-existing, 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 (possibly innate) conceptual
availability. In this study, we have begun using this approach to understand something about how children initially represent and learn a word like *left*. This approach is notably not unique to this study (for example, see Gentner and Boroditsky 2001 for a review of studies on the relationship between early word learning and concept individuation). Adding to this literature, recent training studies in our lab, including this one, indicate that juxtaposing children’s word-learning successes with their failures reveals some dramatic insight into children’s initial conceptual representations. For instance, children have been found to map color and size adjectives with differential ease depending on whether the object at hand is an animal or a food object (Goldvarg-Steingold & Spelke, submitted). Further training studies shed light on the initial constraints on children’s acquisition of spatial reference terms like *north* and *south* as well as *left* and *right* (Shusterman, Li, & Abarbanell, in preparation). Ideally, these studies will help to determine the grain of individual concepts that might get combined in a combinatorial system as well as the boundaries of the domains that house these concepts.

The training methodology confers an additional benefit besides a window onto conceptual structure. Because the experimenter can control how little or how much to teach a child about a given new word, he or she can invite the child to understand the term more narrowly or broadly. This is important for a theory proposing that concepts interact via the combinatorial properties of language. Is there a ‘threshold’ level of meaning that enables an isolated representation to interact with other representations? In the study presented here, only the children who knew *both* meanings of “left” and “right” succeeded on reorientation. Therefore, it seems that levels of meaning do, in fact, govern something about the cognitive consequences of knowing particular phrases.
One goal of this chapter is to offer a preliminary sketch of how such an approach might be applied. Using training data, we have explored how children master different meanings of abstract words like *left*. We have used this analysis to investigate precisely which meanings (or generalizations) are related to a novel capability in spatial reasoning. We posit that this approach can be applied in other domains to investigate other possible relationships between language and thought.

5.3 Specifying the role of language in reorientation: Possibilities and alternate explanations

5.3.1 Does language create a new representation by combining two existing ones? (Alternate possibilities 1 and 2)

How exactly could language come to influence a person’s representation of a spatial environment? In the argument we have been propounding in this chapter, we believe that our language training enabled some children to combine preexisting, encapsulated concepts into one coherent thought. There are at least two coherent alternative explanations to this conceptual combination hypothesis.

One alternative explanation is that the children whom we classified as learners had advantages over the non-learners in the reorientation task aside from the factor of language. For example, perhaps these children were simply better problem-solvers, and therefore succeeded at the language games and the reorientation game independently. Based on Hermer-Vasquez et al.’s (2001) report that IQ and other general problem-solving measures failed to predict reorientation behavior, we speculate that this explanation is not the right one. Even if general problem-solving acuity does underlie success in the reorientation task, problem-solving ability does not solve the
mystery of how those children went about solving the problem and why even good problem-solvers can’t solve the problem earlier than they do.

A second possibility is that our training did influence children’s reorientation behavior, but not through enabling conceptual combination. A different mechanism might suffice for solving the reorientation problem. All that children (or adults) need to do to reorient successfully is to go through a two-step computation: 1) orient to the short red wall or the short white wall (wherever the object was hidden), and 2) choose between the left corner and the right corner 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 either first or second).

Is it possible that our training somehow prompted children to perform the two-step computation suggested in Alternative 2? This does not seem likely. A critical step in this computation is to orient to the correct (i.e. red or white) wall, a step that children dramatically fail to make before they have a complex 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! It is utterly mysterious why learning “left” would help a child pay attention to wall color. Here is one possible explanation: learning a phrase like “to the left of the red wall” might help the child pay attention to the red wall. In other words, maybe 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 spatial description. If this is the right story, then the combinatorial properties of language may indeed be credited with making accessible a piece of information – wall color – that was previously unavailable for this task.
4.2.3 Could language be playing a non-symbolic role? (Alternate possibility 3)

The argument so far rests on the bias, if not the assumption, that language plays a symbolic role in reorientation behavior. The representations contained in the geometric module are presumed to be fully formed; the notion of ‘the corner to the left of the long wall’ is not presumed to be fuzzy or weak. The reason that this representation is not available for interaction with other systems is that it is encapsulated (or so the argument goes). Once the fully formed, encapsulated representation receives an adequate, explicit, symbolic label (i.e., left of the long wall), the label – or symbol – can play a role in natural language sentences in combination with other representations.

An alternative to this view might propose that the function of language in this case is definitively not symbolic. Perhaps language simply makes existing knowledge more explicit by strengthening a previously weak representation. Representations might appear isolated simply because they are too weak to interact with each other or to drive behavior (for an argument of this form, see Munakata 1997). The effect of labeling the hiding location might simply 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. Simply by making both representations more 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 ever encapsulated. The training study does not rule out this possibility.

Alternative 2 suggests that Learners were more able to orient to the correctly colored wall than Non-Learners, and that they were also able to use that information in conjunction with geometric information. Alternative 3 suggests that Learners were more able to explicitly represent and remember the correctly colored wall. Both of these suggestions make the following
prediction: an explicit, verbal representation of the landmark (like the red wall) should make it easier to use that representation during a reorientation task.

To test this possibility, we conducted another experiment using a language cue, instead of language training. 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 children absolutely needed language in order to combine information from encapsulated modules, then the verbal cue would not be expected to help them. However, if children needed help attending to and remembering task-relevant information, such as wall color, then the verbal cue would be expected to help them. The outcome was clear: the verbal cue greatly enhanced children’s performance on the reorientation task [F(2,44)= 6.431, p<.001].

These results are provocative. On the one hand, these data argue against a role for combinatorial language in spatial reorientation; after all, children managed to pass the task without an inkling as to the meaning of left or right. On the other hand, these data might be consistent with a role for language in spatial reorientation; perhaps the effect of learning the phrase “left of the red wall” in the first experiment was to help orient the child to the red wall (as described above), and perhaps this orienting effect was mimicked by the verbal cue in the second experiment.

Why would we argue that these effects reflect the combinatorial properties of a symbolic language, rather than the effect of a more explicit representation? First, the actual words ‘left’ and ‘right’ don’t seem to matter too much in and of themselves: the children who received the verbal cue “at the red wall” searched not only at the correctly colored wall, but on the correct side (left or right) of the correctly colored wall. Therefore, the effect of learning “left of X” must
have conferred a benefit for children in the training study for some reason *other* than granting a simple understanding of the concept *left*. What else could a child gain by learning a phrase like “left of X”? We have argued that this phrase creates an orienting effect to X, the ground object in this spatial description – in our case, a red wall. If so, our language training provided a means to orient to the correct wall by emphasizing the importance of X in a construction like “left of X.” The results of the first training experiment suggest that linguistic combination was critical for reorientation success, because children in the training study who learned the combined phrase succeeded in reorientation, while children who only learned “left” (and already knew “X”) did not. The results of the second experiment suggest that knowing how to orient to the correctly colored wall is all that children need to pass the reorientation task. The results of both experiments taken together support the argument that combinatorial language supplies this necessary orienting cue for children.

6. Summary

In this chapter, we explore the developmental shift in human reorientation, a process that appears 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. We anticipate that further work will eventually elucidate the mechanisms underlying spatial reorientation. In particular, we hope that by elaborating the process of spatial language acquisition, we will be able to provide answers to the many questions about the role of language.

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1 As in, “my left arm”.

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in this developmental shift and extend these hypotheses and methodologies to other tasks and
domains where adult competence transcends the bounds of core knowledge.

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