



Five Reasons to Doubt the Existence of a Geometric Module

Alexandra D. Twyman, Nora S. Newcombe

Temple University

Received 26 August 2008; received in revised form 14 August 2009; accepted 15 August 2009

Abstract

It is frequently claimed that the human mind is organized in a modular fashion, a hypothesis linked historically, though not inevitably, to the claim that many aspects of the human mind are innately specified. A specific instance of this line of thought is the proposal of an innately specified geometric module for human reorientation. From a massive modularity position, the reorientation module would be one of a large number that organized the mind. From the core knowledge position, the reorientation module is one of five innate and encapsulated modules that can later be supplemented by use of human language. In this paper, we marshal five lines of evidence that cast doubt on the geometric module hypothesis, unfolded in a series of reasons: (1) Language does not play a necessary role in the integration of feature and geometric cues, although it can be helpful. (2) A model of reorientation requires flexibility to explain variable phenomena. (3) Experience matters over short and long periods. (4) Features are used for true reorientation. (5) The nature of geometric information is not as yet clearly specified. In the final section, we review recent theoretical approaches to the known reorientation phenomena.

Keywords: Modularity; Adaptive combination; Spatial reorientation; Development; Geometric module

1. Introduction

Love and marriage, horse and carriage, modularity and nativism—the last pair of words lacks the ring of the first two pairs, but the relation in each case is the same. The concepts are different, and each may exist separately and independently, yet they seem for the most part to get along naturally and easily. One expects to see them together. There can be emergent modularity (Karmiloff-Smith, 1992) but that is the marked case, just as a marriage of

convenience is a marked version of marriage (to pursue the analogy). Modularity without modification is generally thought to be inborn (Fodor, 1983; but see Fodor, 2000 for a different view). Similarly, although there can be versions of nativism that are not domain specific (Elman et al., 1996), domain-general learning ability is not what is usually meant by nativism. As generally discussed, nativism is what Elman et al. (1996) call *representational nativism*, and hence is domain specific. And then, once native endowments have domain-specific content, they must have neural instantiations, and those instantiations often seem to involve specialized areas. Voilà—something we would call a module. In fact, it has even been argued that one cannot have an evolutionarily informed cognitive psychology that does not involve modules, because natural selection must have a target on which to act (Cosmides & Tooby, 1992). Against this intellectual backdrop, modules have proliferated—the theory of mind module, the cheater detection module, the face processing module, and so forth. Indeed, we have seen claims that the human mind is “massively modular” (e.g., Carruthers, 2006). This notion has permeated the popular press. For example, consider the following passage from *Newsweek*, “Behaviors that conferred a fitness advantage during the era when modern humans were evolving are the result of hundreds of genetically based cognitive ‘modules’ programmed in the brain,” or “evolutionary psychologists claim that human behavior is constrained by mental modules that calcified in the Stone Age” (Begley, 2009).

The massive modularity position is not the only modularity proposal. Other theorists argue that there are a small number of modules that are the foundation of cognition. One such position is the core knowledge position advocated by Spelke and Kinzler (2007). According to this view, there are five modules that comprise core knowledge: object, action, number, geometry, and social partner representation. In a similar fashion to the Fodorian view of modularity, these modules are domain specific, innately endowed, and shared across species. However, these modules do not persist across the life span from this perspective. According to this point of view, language is the mechanism that moves infants from an innate modular representation to integrated cognition as adults. This core knowledge position is gaining popularity both in the academic and public domains. For example, Vallortigara, Sovrano, and Chiandetti (2009) advocate the core knowledge position, including innate endowment, as a result of their rearing experiments with chicks, writing that “the similarities in cognitive capacities seen near the start of life gives reason to take seriously the hypotheses that core systems have a long evolutionary history and are largely preserved across the many evolutionary events that distinguish chicks from humans” (p. 24). The notion of a limited number of core modules is gaining popularity with the general public as well, although perhaps in the personality not the cognitive domain: “Each of us is born with our own individual level of six big traits: intelligence, openness to new things, conscientiousness, agreeableness, emotional stability and extraversion. These modules are built into humans and other animals (apparently squid can be shy)” (Brooks, 2009).

However, many of the proposed modules, especially those proposed by massive modularity theorists, do not conform to the strict definition proposed by Fodor (1983). Few seem to be encapsulated (i.e., unable to accept relevant information that is not the kind the module is built to process). Most are central to cognition, whereas Fodor thought that modules would involve primarily perceptual phenomena, and that higher-order cognition would prove not

to be modular (and hence, difficult or impossible to study). The word *module* has come to be used in a way that has many connotations but few agreed-upon core characteristics. Indeed, a recent discussion of the meaning of modularity proposed to strip the concept of most of its interesting attributes, including encapsulation, automaticity, neural specialization, and innateness, and yet ended up arguing that such stripping merely clarified the concept, leaving it still valuable because it leads to a focus on function (Barrett & Kurzban, 2006). Given this lack of agreed-upon definition, the modularity position becomes analogous to the Hydra, the many-headed monster that Heracles found difficult to combat because there were too many heads to take on simultaneously, and, worse, because other heads grew while he addressed a specific one.

In this article, we address only one head of the Hydra of modularity: the proposal of a geometric module (Cheng, 1986; Gallistel, 1990; Hermer & Spelke, 1994, 1996). The geometric module has welcome properties from the point of view of engaging in clear debate about modularity. It is well specified, it concerns an interesting aspect of human cognition, and it is increasingly well studied in a variety of species and over development using a variety of techniques. In addition, it has been augmented with an interesting account of how the innately specified module is penetrated in development by the acquisition of specific linguistic terms (Shusterman & Spelke, 2005). Developmental change is always hard for nativists to explain when it is clearly evident yet cannot be dismissed as parameter triggering. In this version of modularity nativism, change occurs because of the supplementary role of another module, the language module. This position is a hybrid of nativism and Vygotskian or Whorfian thinking. Strongly antinativist theorists sometimes cite the hypothesis approvingly, seemingly without realizing its nativist roots (Levinson, 2003).

Versions of the modularity-plus-language account vary in the strength. Some can be characterized as a strong view of modular cognition (Spelke & Kinzler, 2007). Other versions of the modularity-plus-language positions are gaining momentum. One example is the Momentary Interaction hypothesis, advocated by Landau and Lakusta (2009). In this version, reorientation is still accomplished primarily by a geometric module; the properties of reorientation “fall within the criterion that Fodor proposed for modular systems, in particular, domain-specificity, localization, ontogenetic invariance, and characteristic breakdown patterns” (p. 3). The Momentary Interaction hypothesis differs from modularity-plus-language, however, in its view of language. From the modularity-plus-language view, language radically alters the cognitive representation of the human mind. While language still plays a role in the Momentary Interaction hypotheses, it is viewed as a less powerful tool. Within this account, language serves as an attention tool that is a “flexible and powerful enhancement of spatial representations through language, but not through radical restructuring” (p. 3).

Core knowledge and modularity-plus-language provide an interesting and tantalizing perspective on the ontogeny of knowledge. Nevertheless, there is good reason to doubt the validity of this approach. This article reviews reasons for doubt. We begin by briefly defining the geometric module and the core research that initially defined it. We proceed to discuss five reasons to question its existence (or perhaps more precisely, four reasons and a counterargument to a recent claim made by modularity proponents). These five reasons, and

Table 1
Five reasons to doubt the existence of a geometric module

Five Reasons

1. Language does not play an essential role in the integration of feature and geometric cues
 - (a) Nonhuman animals are able to use geometric and feature cues
 - (b) Adults' feature use is not uniquely dependent on language
 - (c) 18-month-old children can integrate geometric and feature cues in large spaces
 2. A model of reorientation requires flexibility to explain variable phenomena
 - (a) The relative use of geometric and feature information depends on room size
 - (b) Flexibility to predict when overshadowing and blocking will or will not occur
 3. Experience matters over short and long periods
 - (a) Short-term training experiments demonstrate plasticity
 - (b) Rearing experiments demonstrate plasticity
 4. Features are used for reorientation: Evidence against a recent two-step model
 - (a) Reorientation in an octagon
 - (b) Features are used as landmarks for indirect orientation
 5. Redefining the analysis of geometric information
 - (a) Not all kinds of geometry are used early in development
 - (b) Use of scalar and nonscalar cues by toddlers
 - (c) Use of scalar and nonscalar cues by mice
-

their related subpoints, are summarized in Table 1. This review builds on the literature review by Cheng and Newcombe (2005), but it includes recent papers written since that review and is also more critical and selective in nature. It should be read in conjunction with Cheng (2008), an article in which the original proposer of the geometric module also questions the status of the hypothesis. In the last section, we discuss alternatives to modularity theory, as there are now several proposed theories of the relevant phenomena.

2. The geometric module proposal

Mobile creatures need to be able to navigate efficiently through their environment. Occasionally, we lose track of our position in the world, for example, after tumbling down a hill or emerging from a subway system. Before we are able to continue with the task at hand, for example, finding our way home or to work, we need to re-establish knowledge of our position in the spatial world, in a process known as reorientation. The scientific study of this domain started with the seminal work of Ken Cheng (1986). The experiments in his paper showed a rather odd pattern of behavior in disoriented rats. The search space was a rectangular arena full of multimodal features (including distinct odors, lights, patterned panels, or colored walls). In a working memory task, the rat found a food reward and then was removed after eating only a portion of the treat and immediately transferred to an identical enclosure. The crucial observation was where the rat searched for the remaining food. Surprisingly, the rat only returned to the correct location about half of the time. The other half of the time, the rat went to the diagonally opposite position, which might, for example, smell of peppermint when the rewarded place had smelled of licorice. Apparently, the only information being used from the

search arena was geometric information about its shape. As shown in Fig. 1, by combining geometric and sense information, the rat can narrow search for food to the corners with the long wall to the right and a short wall to the left (or vice versa). Although feature information would double the frequency of reward, in working memory tasks (when the correct corner changes from trial to trial) rats reoriented using geometric information to the exclusion of feature cues. However, when the reinforced corner stayed the same across training sessions, in a reference memory task, the rats learned to use feature information.

Cheng (1986) proposed the idea of a geometric module to explain this phenomenon. Reorientation is accomplished first on the basis of metric information and then nongeometric information can be pasted onto this metric frame. This conclusion was subsequently extended to a different task, a different stimulus array and a reference memory situation. In a water maze task, Benhamou and Poucet (1998) demonstrated that rats are able to extract geometric information from an array of discrete and unique landmarks. The landmarks were placed in a circular pool and arranged as the vertices of either an equilateral or isosceles triangle. Even when the geometric information of the isosceles triangle had to be extracted from the separated points in the array, it was still much easier for the rats to learn the location of the hidden platform from geometric than from featural information. Thus, it seems that rats rely primarily on geometric information for reorientation and use feature information only secondarily, if at all.

Gallistel (1990) proposed an evolutionary account for the primacy of geometric information. He noted that many features change from season to season, such as the color of the foliage, or even day to day, such as the clarity of a river, but that geometric information remains much more constant, stable, and reliable, so that it may be evolutionarily adaptive to reorient based on the invariant properties of the environment. Another point to consider is that geometric ambiguities may not arise often in the complex natural world. Thus, even though in experiments animals may be rewarded only half the time when they reorient using only geometric information, in a naturalistic setting the payoff for using geometric information is probably much higher.

Subsequent to this work with rats, researchers asked what human capabilities are and how they appear in ontogeny. Evidence appeared that there seemed to be a developmental

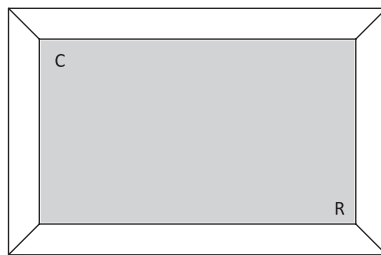


Fig. 1. A schematic of a typical rectangular enclosure for the reorientation studies. The organism finds a food reward at the correct corner, C. On the basis of geometric information, the diagonally opposite corner, R, is equivalent to the correct corner. As an example, the short wall is to the creature's left and the long wall to the right at both the correct and rotationally equivalent corner.

progression for reorientation, from exclusive use of geometric cues early in life, to a more flexible system later in development. At 18–24 months of age, children do not spontaneously use feature information for reorientation in small rectangular spaces, but readily use geometric information (Hermer & Spelke, 1994, 1996). Similarly, disoriented 12- to 18-month-old infants cannot use distinctive landmarks to localize a peekaboo event (Lew, Foster, & Bremner, 2006). For children at or above the age of 6 years as well as adults, feature and geometric information are flexibly combined (Hermer-Vazquez, Moffet, & Munkholm, 2001).

The modularity-plus-language hypothesis proposed that people are able to penetrate the geometric module for reorientation that we share with other animals with the production of spatial language (Shusterman & Spelke, 2005). The hypothesis was supported by relations between the age at using features and the productive capacity to use the terms “left” and “right” (Hermer-Vazquez et al., 2001), by findings that adults prevented from using language to encode the space by a concurrent linguistic task failed to use features (Hermer-Vazquez, Spelke, & Katsnelson, 1999), and by demonstrations that linguistic reminders and training elicited earlier use of features (Shusterman & Spelke, 2005). Additionally, spatial linguistic cues of “left” or “right” aid 4-year-old children’s performance on a left-right color location memory task (Dessalegn & Landau, 2008). Taken together, the findings from rats, children, and adults seem to present a formidable case for the existence of an encapsulated module that runs automatically, appears early, and is shared across mobile species, with developmental change in humans due only to the intervention of a specifically human capability, namely language.

Fueled by the interest that the geometric module generated, many investigators have examined reorientation over the past 20 years. Although we call the geometric module into question, we would like to point out that the hypothesis has provided a solid starting place for studies of reorientation and still pushes the field to refine its empirical paradigms and theoretical positions. Over the last decade, considerable amounts of counter-evidence have appeared, collectively casting a substantial shadow on this modular picture of development and of the architecture of spatial adaptation. Nevertheless, the data serve to constrain the search for alternative conceptualizations of spatial functioning and its development, and recently, several models have been proposed that contend to explain the relevant phenomena.

In overview, we discuss five reasons to doubt the existence of a geometric module. First, we address the language part of the modularity-plus-language position, discussing reasons to doubt that language plays a unique role in the integration of feature and geometric information. There is evidence that nonhuman animals flexibly use geometric and feature cues for reorientation, that human adults’ reorientation ability is not dependent solely on language, and that toddlers are also able to flexibly use geometric and feature information in larger spaces before they possess the relevant language. Second, we review variability in the geometric module phenomena, including the fact that geometric and feature cue use depend on environment size, and that overshadowing, blocking, and facilitation effects have all been observed. These examples show that any successful theory of reorientation must be flexible enough to explain these fluctuations, a difficult challenge for a modularity or core knowledge position. Third, the core knowledge approach postulates that the reorientation

system is innate, and thus downplays the effects of experience on the behavior of reorienting organisms. In contrast to this hypothesis, we demonstrate that experience, both in short-term training experiments and over the long term in rearing experiments, has an important influence on the orientation performance of participants. Fourth, we turn to a recent two-step model of reorientation. Here, advocates of the core knowledge position argue that geometric information is used alone for true reorientation, although subsequently, features can be used associatively to pinpoint a goal location. In contrast, we review evidence that features can be used for true reorientation, both in the presence and absence of geometric information. Finally, we discuss what types of geometric information can be used across development and across species for reorientation. It has become apparent that not all types of geometry are used for reorientation, and that a more specific definition of geometric information is needed. A summary of these five reasons can be found in Table 1.

3. Reason 1: Language does not play an essential role in the integration of feature and geometric cues

Initially, there seemed to be quite a bit of evidence to support the hypothesis that language plays a fundamental role in the integration of geometric and feature information. When Hermer and Spelke (1994, 1996) first adapted the reorientation paradigm for use with people, children below the age of 6 years did not use feature information in small spaces. In contrast, older children and adults are able to flexibly combine geometric and feature information. Human language (and in particular the productive use of the spatial relational terms “left” and “right”) was proposed to puncture the geometric module that we share with other species (Shusterman & Spelke, 2005). Additionally, language training interventions facilitated children’s use of features. However, there are three kinds of evidence that cast doubt on the hypothesis that language plays an essential role in the integration of geometric and feature cues.

3.1. Nonhuman animals use features for reorientation

On the modularity-plus-language view, nonlinguistic species should clearly have difficulty using feature cues for reorientation. Since the initial work with rats and young children, a wide range of vertebrate species have been studied, including chickens, pigeons, monkeys, and fish, in both appetitive and escape reorientation paradigms, and there are many demonstrations of use of feature cues (see Cheng & Newcombe, 2005 for a review). Recently, an invertebrate representative, the ant, has also been demonstrated to use feature as well as geometric cues (Wystrach & Beugnon, 2009).

There are important distinctions among feature cues, however, that need to be examined to put these data in context. Features may be direct markers of the target location (sometimes called beacons), or they may be indirect markers of a goal location (sometimes called landmarks). In many of the experiments cited above, the experimental paradigm or data analyses did not distinguish between using the feature cue as a beacon or as a landmark. For

example, in a rectangle with discrete feature panels, the feature cue could be used either as a beacon or as a landmark (Fig. 2A). Participants learn that a reward is hidden in a particular corner, near the black panel in this example. After participants are trained to perform well on the task, follow-up tests can be conducted. One of these types of tests, the distal test in Fig. 2C, is particularly useful for distinguishing between features used as landmarks versus beacons. After training, the target feature panel and the rotationally equivalent panel are removed. Therefore, for the participant to be able to return to the correct corner, the distal feature cues must be used, and thus successful search indicates that features can be used as landmarks for reorientation. However, if the black panel is retained, successful search can be based on a beacon strategy. This distinction may seem to be a minor point; however, it is quite important. When there are markers of a specific location (i.e., a beacon), the participant may or may not be using an associative process to guide search, that is unrelated to the reorientation process. In contrast, indirect feature use is strong evidence that features are used to guide the reorientation process, rather than just search strategies.

There has been mixed evidence of use of features as landmarks as well as beacons in geometric module research with nonhuman animals. Pigeons are successfully able to return to the target corner on distal panel tests (Kelly, Spetch, & Heth, 1998). Thus, features can be used as landmarks (rather than just beacons), and this process does not critically depend on language. In contrast, rats, mice and chicks divide search between the two geometrically equivalent corners (Cheng, 1986; Twyman, Newcombe, & Gould, 2009; Vallortigara, Zanforlin, & Pasti, 1990). Therefore, for rats, mice, and chicks, it is only clear that features can be used as beacons. It is also possible that features could be used as landmarks with these species, with altered experimental parameters. As the other feature panels were not explicitly required for the task, it is possible that subjects ignored the other feature panels and did not encode them into their spatial representation. Thus, manipulations that draw

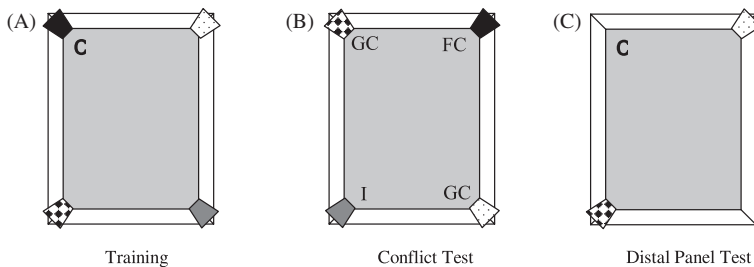


Fig. 2. Typical tests for reorientation paradigms. After training with a feature (A), various follow-up tests are conducted to examine how features and geometry are used. In the conflict test (B), an affine transformation is achieved by rotating each panel one position, clockwise in this example. Now, the correct feature corner (FC) is no longer in a geometrically correct position. The animal may choose to visit either a featurally correct corner or one of the two geometrically correct corners (GC). The animals usually avoid the incorrect corner (I) as it is neither featurally nor geometrically correct. Finally, it is possible that participants could have used either the local features (the panel at the target location—as a beacon) or the distal features (the panels at the other corners—as indirect landmarks) to reorient. This is tested by removing the feature panels at the two geometrically equivalent corners and then observing whether the animals are able to focus their search at the previously trained corner by using the remaining feature information indirectly, as we can see in panel (C).

attention to the nonreinforced feature panels (perhaps by expanding the search size, and therefore making the features more distal) may demonstrate that even for rats, mice, and chicks, features can be used for reorientation as both beacons and landmarks. In sum, while the use of features as landmarks (rather than just beacons) remains an open question for some species, it has been clearly demonstrated that pigeons can use features as landmarks, and this process does not critically depend on language.

An additional argument for the geometric module-plus-language position argues that geometric cues should be more readily used for reorientation than feature cues (either beacons or landmarks). Evidence from the animal literature demonstrates that there are instances where feature information can rival the strength and utility of geometric information, as revealed through conflict tests (Fig. 2B). In conflict experiments, feature and geometric cues are put in opposition by rotating the feature cue, so that the correct feature corner is in a geometrically incorrect position (Fig. 2B). Some animals divide search between the two geometrically equivalent corners and the one featurally correct corner. This is true for mountain chickadees, pigeons, and redbtail splitfin fish (Gray, Bloomfield, Ferrey, Spetch, & Sturdy, 2005; Kelly et al., 1998; Sovrano, Bisazza, & Vallortigara, 2007). Moreover, some animals choose the featural corner over a geometrically correct one. For chicks, this was true only when the features directly marked the correct location (as a beacon, as discussed above) (Vallortigara et al., 1990). Rats follow the feature to a geometrically incorrect corner, which is perhaps surprising as the strongest evidence for a geometric module has been found for this particular species (Wall, Botly, Black, & Shettleworth, 2004). Thus, there appear to be many instances where feature information can rival the strength and utility of geometric information.¹

Why is there a contrast with the original Cheng findings—that rats seemed to exclude nongeometric information—while many other nonhuman animals (and perhaps even rats) can use feature information for reorientation? It was originally proposed that the geometric module operates only in working memory tasks (as the defining pattern of rotational errors was only found when the target corner changed from trial to trial) in Cheng's (1986) work. All other tests of reorientation in nonrat species have been done with a reference memory paradigm. There are several problems with this argument, however. First, Benhamou and Poucet (1998) found the encapsulation effect in a reference memory task with rats. Second, the work with human children has used a reference memory paradigm too, so the contact between the animal and the developmental literatures is tenuous if the importance of working memory is stressed. Third, it is hard to see how reorientation in the natural world is less important when stable (reference memory) rather than variable locations (working memory) must be retained. That is, a module that operates in working memory but not reference memory would seem to be comparatively insignificant from an adaptive point of view. Nevertheless, the existing findings can be largely (if not completely) reconciled if one accepts that encapsulation is only evident in working memory paradigms.

Advocates of the modularity position also argue that the extensive training required to test reorientation in animals supports learning of a different nature than possible with a linguistic toolkit. For instance, Hermer-Vasquez et al. (2001) wrote that “no result has yet conclusively shown that nonhuman [animals] show the spontaneous, flexible indirect landmark use found with human adults' reorientation” (p. 267). Pigeons have been

demonstrated to use landmarks indirectly as reorientation cues (Kelly et al., 1998). However, training is still required for pigeons to perform that task, and thus the reorientation ability of extensively trained animals may be different from the spontaneous reorientation ability of people. Thus, we turn to work with humans.

3.2. Adults' feature use is not uniquely dependent on language

One of the most striking findings supporting the modularity-plus-language position is Hermer-Vazquez et al.'s (1999) finding that human adults required to do a verbal shadowing task (but not a control task that seemed equally attention-demanding) fail to use a feature as large as a colored wall to guide search. Without access to language, they seem to revert to the core knowledge mode of functioning, similar to that of children and nonhuman animals. However, it is possible that the verbal shadowing task used by Hermer-Vazquez et al. (1999) might disrupt the ability to use featural landmarks not (or not only) by interfering with a linguistic encoding process within a geometric module. The nonverbal rhythm-clapping task used by Hermer-Vazquez et al. (1999) is ill-suited to control for this possibility because it involves primarily cerebellar regions of the brain (Woodruff-Pak, Papka, & Ivry, 1996) and would not be expected to engage spatial coding systems. A nonverbal *spatial* task might interfere with the integration of geometric and featural information in the reorientation task.

In confirmation of this idea, Ratliff and Newcombe (2008a) found that participants required to verbally shadow while doing the reorientation task were less likely to use features to reorient, just as Hermer-Vazquez et al. (1999) had reported, although not reduced to chance levels. A nonverbal spatial task also produced a similar dampening effect on the use of features. Hupbach, Hardt, Nadel, and Bohbot (2007) also report that a spatial as well as a verbal task impairs spatial reorientation, and they found that verbal shadowing did *not* disrupt use of features in a square environment. Taken together, these studies strongly suggest that language is not crucial in combining information from geometric and nongeometric sources in order to reorient, although it may sometimes be helpful. Instead, the combination of featural and geometric information may depend on cognitive and neural mechanisms that are involved in both spatial and verbal attention and memory (Newcombe, 2005).

3.3. Young children can flexibly integrate feature and geometric cues in larger spaces

Although more complete discussion of the effect of room size will follow in reason 2, a preview of this reason is essential to reviewing the role of language in feature use. The initial studies of human toddlers were conducted in very small environments. When the scale of the space is increased, even by as little as to double the dimensions of each wall, children as young as 18 months are able to flexibly integrate geometric and feature cues. Children of this age are not yet able to produce the spatial terms "left" and "right," which has been claimed to predict success at using the feature wall for reorientation (Shusterman & Spelke, 2005). Thus, there is reason to doubt that language penetrates the geometric module for children.

3.4. Summary

In summary, there is substantial evidence to doubt that language is crucially important for the integration of geometric and feature information in humans. First, nonhuman animals have been demonstrated to flexibly combine geometric and feature information, sometimes preferring feature information, and pigeons (at least) can use landmarks as indirect reorientation cues. Second, for human adults, although language can be a tool for reorientation, it is not a necessary mechanism for successful reorientation. Finally, children as young as 18 months old, before they are able to produce relevant spatial language, are able to flexibly integrate geometric and feature cues under certain conditions. Thus, there is reason to doubt that language is required to penetrate the proposed geometric module for reorientation.

4. Reason 2: Models of reorientation require flexibility to explain variable phenomena

Since the early experiments of Cheng (1986) and Hermer and Spelke (1994, 1996), many studies have shown that some of the crucial phenomena depend on the parameters of the experiment. These facts are difficult to explain from a core knowledge or modularity position. In the text that follows, we will review the two central phenomena: room size effects, and the presence and absence of overshadowing, blocking, and potentiation effects.

4.1. *The relative use of geometric and feature information depends on room size*

Features are more likely, and geometric cues are less likely, to be used for reorientation as the size of the enclosure increases. Importantly, the room size effect is common across children, adults, and nonhuman species. Thus, the room size effect may depend more on the salience of the cues, rather than development or cross-species difference per se.

4.1.1. *The room size effect for children*

Hermer and Spelke's (1994, 1996) original experiments made an odd choice of experimental environment, given that the overall aim of research in spatial orientation is to understand how we manage to navigate in natural environments, which are generally fairly large. Specifically, they used a rectangular enclosure that was only 4 feet by 6 feet in size. In a space with walls of length in the same proportional relationship (8 by 12 feet), but with four times the square footage, Learmonth, Newcombe, and Huttenlocher (2001) found that children of 18–24 months succeeded in using a variety of features to reorient, including features that only indirectly mark the correct corner. Learmonth, Nadel, and Newcombe (2002) confirmed the central role of scale, manipulating room size in an experiment with preschool children. More recently, Smith et al. (2008) also showed the importance of scale, manipulating array size in a naturalistic environment. Children between the ages of 3 to 7 years were able to successfully reorient with feature cues, although performance increased with age. Additionally, the size effect was replicated in this natural environment, as children were more accurate using feature information in the larger arrays than the smaller arrays.

However, it should be noted that the Smith et al. experiment was conducted outside, and hence the study was not able to control for potential confounding cues such as the position of the sun. Nevertheless, the study represents an important extension to studying how orientation might be guided in a naturalistic setting. Even the “larger” room used in the Learmonth research is not very large, in terms of the real world. Thus, for children, feature cues appear to only be neglected in small spaces.

4.1.2. The room size effect for adults

Does the room size effect that was demonstrated for children hold for adults? Ratliff and Newcombe (2008b) provide evidence that room size influences human adults' use of geometric and feature cues. Adults participated in four trials in either a small or a larger rectangular room with a feature panel. After the training trials, the adults were administered two conflict trials in the same sized rectangle. Thus, adults who were trained in the small room were administered the conflict trials in the small room and adults who were trained in the large room participated in the conflict trials in the large room. Adults who were in the small room group selected a geometrically correct corner, while adults in the larger room group decided to go with the featurally correct corner. Thus, it appears that for humans, children and adults alike, the size of the room is a vital determinant of when geometric and feature cues are used for reorientation.

4.1.3. The room size effect for nonhuman animals

The role of enclosure size has also been confirmed in experiments with nonhuman animals, specifically chicks, fish, and rats. Chicks trained to find food at a distinctive panel in either a small or a large rectangle showed higher use of feature information when trained in the larger one (Chiandetti, Regolin, Sovrano, & Vallortigara, 2007). Room size also influenced decisions in conflict situations. In the large room, the chicks followed the feature, while in the small room, the chicks divided their search between the two geometrically equivalent corners (Sovrano & Vallortigara, 2006). Redtail splitfin fish showed similar patterns (Sovrano et al., 2007). Similarly for rats, increasing the size of the enclosure resulted in increased attention to the feature wall, and decreasing the enclosure size increased attraction to the geometric cue (Maes, Fontanari, & Regolin, 2009). Thus, there seems to be something about the experimental parameters that increases geometry use in smaller spaces and augments feature use in larger spaces.

4.1.4. Possible reasons for the effect of room size

Why does the enclosure size matter? There are several possible explanations for the room size effect. First, it is possible that the two sources of information are not combined in a small space because the small space restricts movement. Restrained rats do not seem to learn the same information about a maze that freely moving rats do (Foster, Castro, & McNaughton, 1989), and children perform more accurately when they are actively moving, rather than passively moved (Acredolo, 1978; Acredolo & Evans, 1980; McComas & Dulberg, 1997). Additionally, geometric information may be more dominant in small enclosures because the lengths of the walls, and aspect ratios, are more easily observed (Sovrano

& Vallortigara, 2006). Second, distal rather than proximal features provide more precise information about location as movement occurs (Gallistel, 1990; Nadel & Hubbach, 2006; Vlasak, 2006). In the large room, the blue wall is (often) farther away and could be a sufficiently distal cue to be weighted more heavily by the reorientation system. It is possible that this effect may reflect the underlying properties of hippocampal place cells. Place cells are particularly attuned to distal features, rather than proximal cues (Cressant, Muller, & Poucet, 1997), and this may be why feature use increases with increasing apparatus size. Additionally, as the size of the testing space has now been shown to affect the location of hippocampal firing in exploring rats (Kjelstrup et al., 2008), greater attention to spatial scale in studies of spatial functioning is clearly warranted across a wide range of species.

Learmonth, Newcombe, Sheridan, and Jones (2008) report a series of experiments designed to examine what processes might support the room size effect. Specifically, the role of restricted movement and landmark distance was examined for young children between the ages of 3 and 6 years. The basic principle of these experiments was to restrict children's activity to an area the size of the small space used in the Hermer and Spelke (1994, 1996) experiments, within an area the size of the larger space used in the experiments by Learmonth et al. (2001, 2002). Although the children's motion was restricted to the small space, they had visual access to a larger space, containing a distal feature, and with its characteristic aspect ratio. Table 2 summarizes the findings regarding ages at which features are first used to reorient as a function of whether children could move freely in the space, whether the colored wall was distally located in a larger enclosure, and a third factor that turns out to be important—whether the target for which children searched after disorientation was adjacent to the feature. Comparing across studies in which two of these factors were constant allows us to draw inferences regarding whether the third factor affects the age at which successful use of features is first observed. From the contrast between rows 2 and 4 in Table 2, we can infer that restriction of movement has a powerful effect on children's ability to use the landmark to reorient, as children that are able to move freely are able to use the feature at 18 months of age, where children with restricted motion cannot use the feature until 4 years of age. Similarly, the contrast between the Hermer and Spelke (1994, 1996) studies and Experiments 2 and 3 in Learmonth et al. (2008) (rows 1 and 4 in Table 2) shows that whether the colored wall was distal from the child in a larger room has an important effect on children's ability to use the landmark to reorient, namely children can use

Table 2
Age of success in rectangular spaces as a product of variations in the task demands

Experiment	Colored Wall Distal?	Action Possible?	Target Proximal to Colored Wall?	Age of Success
Hermer & Spelke	No	No	Yes	6 years
Learmonth et al.	Yes	Yes	Yes	18 months
Experiment 1	Yes	No	No	6 years
Experiments 2 and 3	Yes	No	Yes	4 years
Experiment 5	Yes	Yes then No	Yes	3 years

Note. From Learmonth et al. (2008, p. 423). Reprinted with permission.

distal features earlier (4 years) than proximal features (6 years). Finally, the comparison between Experiment 1 and Experiments 2 and 3 in Learmonth et al. (2008) (rows 3 and 4 in Table 2) shows that whether the target was located adjacent to that wall or one of the white walls in the larger enclosure is important, in that correct searches with a distal feature appeared earlier in development when the target was directly adjacent to the feature wall (4 years) than at an all-white corner (6 years). Thus, the ability to move around and the presence of distal (rather than proximal) features are two properties of larger spaces that enable children to use features at younger ages in development.

4.1.5. *Summary of room size effects*

Across a wide range of species, the size of the search space matters for reorientation. For all ages of people, and across species, geometry is used more predominantly in small spaces, and feature information in larger spaces. This room size has empirically been demonstrated to hinge on at least two important principles: Movement enhances spatial navigation, and distal landmarks are more likely to be used for reorientation. For the modularity position to be able to explain the room size effects, it would have to propose that reorientation is only modular in small spaces. It would then be a challenge to imagine why it would be advantageous to have a modular system in small spaces, when navigation through the environment occurs on a much larger scale.

4.2. *Fluctuating findings on overshadowing, blocking, and facilitation*

In addition to the fluctuating integration of feature and geometric cues based on room size, research has found a variable presence versus absence of overshadowing, blocking, and facilitation effects that is difficult to explain on a modularity view.

4.2.1. *Principles of associative learning*

First, let us review a few of the principles of associative learning. In overshadowing, when predictive cues are presented together, less may be learned about each cue than if they had been presented independently. For example, if a bright light and a faint tone predict a food reward, the more salient bright light *overshadows* the faint tone. As a result, the light controls behavior while the tone does not control behavior, although the faint tone would have been learned if presented on its own. In spatial tasks, beacons (landmarks at the goal location) can overshadow more distal landmarks, as has been demonstrated for rats (Diez-Chamizo, Sterio, & Mackintosh, 1985) as well as pigeons and humans (Spetch, 1995). In blocking, if a particular cue is learned first, and then is subsequently paired with a second cue, the second cue is not associated with the reward. For example, the participant first learns that one cue, such as a light, is predictive of a reward. Then the light is presented with a second cue, such as a tone. Even though both the light and the tone are equally predictive of reinforcement, the past learning history of the organism *blocks* the learning of the new cue. The principle of blocking also seems to apply to the spatial domain since blocking has been demonstrated in landmark learning with oriented rats (Biegler & Morris, 1999; Roberts & Pearce, 1999; Rodrigo, Chamizo, McLaren, & Mackintosh, 1997).

4.2.2. *Associative learning and the reorientation paradigm*

Do the principles of overshadowing and blocking hold for reorientation? Initially there were reports of a failure to find the traditional associative learning effects for geometric cues. Feature cues did not seem to block the learning of geometry. Wall et al. (2004) trained rats to find food in a square arena where one black feature panel indicated the food location. Once the rat learned to find the food, the black panel was presented within a rectangular search arena. Blocking would predict that the rats would not encode the geometry of the space because they already know that the black panel predicts food location. In contrast, geometry-only test trials revealed that the rats were able to use the geometric information for reorientation.² Additionally, feature cues did not seem to overshadow the learning of geometry (Cheng, 1986). These findings were taken as strong evidence for the modularity position. As the cues were not interacting with each other, it would seem that geometric information is processed at least separately, if not exclusively, from feature information.

However, an absence of overshadowing or blocking effects is not always observed in studies using feature and geometric cues. For rats, both overshadowing and blocking have been demonstrated. Rats were required to find a submerged platform in the corner of a rectangular arena with a feature wall. If the feature wall had previously been trained, then the feature blocked the learning of the geometry. When the feature wall was presented together with the geometric information, then the feature information overshadowed the geometric information (Pearce, Graham, Good, Jones, & McGregor, 2006). Additionally, in a recent set of experiments, a failure to find blocking of geometry by a beacon that was suspended over the platform was found when 12 blocking sessions were administered, although if the blocking sessions were doubled to 24 sessions, then the beacon cue blocked the geometry of the enclosure (Horne & Pearce, 2009). For mountain chickadees, when the blue feature wall was adjacent to the food reward, the geometry-only probe trials revealed that the chickadees had not encoded the overall shape of the arena. Thus, feature information overshadowed geometric information for this species in some training situations (Gray et al., 2005, but see Batty, Bloomfield, Spetch, and Sturdy, 2009, for black-capped chickadees).

It has recently been found that features can even augment (rather than block or overshadow or have no effect on) the acquisition of geometry cues, in a phenomenon called potentiation or facilitation. Rats searching for a hidden platform in an enclosure shaped like a kite did better on a geometry-only test if trained with both feature and geometric information than if trained only with geometry (Graham, Good, McGregor, & Pearce, 2006). Hence, there is evidence that the two types of orientation cues interact with each other, and this is difficult to explain from a modular position.

4.2.3. *How should traditional association effects, or a lack thereof, be interpreted?*

How should association effects be used? Are they gold standards that can support or refute a modular system? If so, then clearly the results are quite mixed. Or are they variable phenomena that should be explainable and predicted by a theoretical position? We discuss this point further in the last section, as at least one current model of the findings was developed specifically to account for variable effects.

However, let's now move up in our level of analysis. There has been a long debate in the broader field of spatial cognition concerning whether mobile organisms navigate with response learning or place learning (Hull, 1943; Tolman, 1948). A large part of this debate has centered on the success or failure to find associative learning. On one side, the response learning tradition has found instances of associative effects (Hamilton & Sutherland, 1999). On the other side, place learning theorists, or cognitive map theorists, have failed to find blocking and overshadowing, as predicted by their theoretical position (Hardt, Hupbach, & Nadel, 2009). The cognitive map approach proposes an explanation for the existence of blocking and overshadowing effects, centered on the role of exploration. When participants are allowed opportunities to explore, then cognitive map theorists maintain that the organism is spontaneously, independent of reward, creating and updating a cognitive map. Thus, when blocking and overshadowing effects are found, this theory proposes that participants have not been given an opportunity to explore, and thus a cognitive map was never formed during the experiment and the participant manages as best he/she can through associative learning.

The important point here is that, in this debate, a failure to find blocking and overshadowing is taken as support of a cognitive map—a unified representation. In contrast, in the reorientation debate, a failure to find blocking and overshadowing is taken as support of a modular system. Thus—should blocking and overshadowing be used as a gold standard? We would like to argue, in light of what we have just reviewed, that it would be a more fruitful approach to acknowledge that the most productive line is to determine the conditions that lead to the variety of findings. This variation is one of the facts in this literature that a successful theory should be able to explain, and modularity theory clearly does not have the required flexibility. At the same time, as we explain later in the article, some of the theories that do not assume modularity (e.g., Miller & Shettleworth, 2007; Newcombe & Ratliff, 2007) can successfully handle this flexibility.

4.3. *Summary*

Since the early experiments of Cheng (1986) and Hermer and Spelke (1994, 1996), many studies have been conducted. In the first section, it was demonstrated that the size of the reorientation enclosure drove the relative use of geometric (in small spaces) and feature (in larger spaces) cues. This phenomenon was found across development and across species. Larger spaces allow for movement that makes it easier to form an integrated representation of the space, and distal features are more likely to be integrated than proximal features. The second section reviewed the presence or absence of blocking, overshadowing, and potentiation effects. A failure to find these associative effects initially supported modularity, as it demonstrated that feature and geometric cues were not interacting with each other. However, future research demonstrated that under certain conditions, blocking, overshadowing, and even potentiation effects have all been found for spatial reorientation. The core knowledge or modularity positions do not have the flexibility to explain either kind of fluctuating phenomena. Next, we turn to the role of experience in reorientation behavior.

5. Reason 3: Experience matters over short and long durations

The modularity position predicts that reliance on geometry alone should be difficult or impossible to modify (except by the intervention of language) and in fact, language training does work to help children use features (Shusterman & Spelke, 2005). However, training effects not dependent on language have been found for adults, young children, and pigeons. In addition, rearing conditions seem to be important. Here we review data that indicate that experience matters both in short-term training studies and for long-term rearing studies.

5.1. Training experiments

Training experiments have been conducted with quite a range of participants, including adults, children, and pigeons. In all of these studies, short-term experience influenced reorientation. Ratliff and Newcombe (2008b) provide evidence that training affects human adults' use of geometric and feature cues. Adults participated in four training trials in either a small or a larger rectangular room with a feature panel. After the training trials, the adults were administered two conflict trials in the opposite sized room (for example, adults who had been trained in the small room were tested in the large room). For adults trained in the larger room and then tested in the small room, the first choice was often to the featurally correct corner. In addition, for adults who practiced the task in the small room, where geometry is more salient than features, and then were tested in the larger room, the conflict choice was also to the featurally correct corner. Thus, there is an asymmetric relationship between the trainability of feature and geometric information for adults. If training were to have an equal effect on the conflict trials, then one would have predicted that practice using geometry in the small space would have transferred to the larger space, but this did not occur. It is possible that the participants did not trust the enclosure information after a change in scale. On these conflict tests, the feature remains unchanged from training to testing. Even though the ratio of the long to short walls was held constant across expansion or contraction, participants did report noticing the change in enclosure size and thus may have relied more heavily on the feature information. Regardless, adults' responses were influenced by the short-term experience.

Training effects have also been found with young children (Twyman, Friedman, & Spetch, 2007). Four and five-year-old children are not normally able to integrate feature and geometric information in small, 4×6 foot enclosed spaces. However, after a small number of training trials, between 4 and 12 trials, these young children are able to flexibly integrate feature and geometric information in small enclosures. This training is equally successful when practice with the feature cue is administered in presence (rectangle) or absence (equilateral triangle) of unique geometric cues. Similar findings are reported by Learmonth et al. (2008, Experiment 5) who used four trials of training in the larger room, and then found feature use in the small room. Thus, children's prior experience influences the relative use of feature and geometric information. For the core knowledge position (Kinzler & Spelke, 2007; Spelke & Kinzler, 2007), each of the five systems is characterized by signature limitations or cognitive errors. It is difficult to imagine that the limited number of training trials,

as few as four, would be sufficient to overcome the characteristic limitation as outlined from the core knowledge position, which are claimed to persist into adulthood, albeit in attenuated and more flexible forms.

Pigeons' choices are also affected by their training regimen, and these effects are clearly not dependent on language. When pigeons are trained with rectangular geometry alone, and then given subsequent trials in which features are added and features and geometry are put into conflict, they divide their search between the geometric and feature corners. When both geometry and feature cues were present from the start of training, the pigeons followed the feature panel in conflict trials (Kelly et al., 1998). These findings suggest that geometry is used in conflict situations only when it has had the advantage of initial training alone, whereas features are used even without that advantage. Therefore, short-term reweighting of the relative use of feature and geometric information for reorientation has been demonstrated for adults, children, and pigeons.

5.2. Rearing conditions count

If short-term exposures in the laboratory influence use of geometry versus features, it seems reasonable to suppose that an organism's natural environment will also influence its behavior, perhaps especially the characteristics of the environment to which an immature organism is exposed. Many of the species that have been tested for their use of geometry have been raised in the geometrically regular environments of laboratories or houses. Would use of geometry be as prevalent when organisms have been exposed to environments with few regular geometric enclosures? This question was raised by Cheng and Newcombe (2005), and there are now several studies that attempt to answer it, with birds, fish, and mammals.

Gray et al. (2005) examined the use of feature information in wild-caught chickadees from forested mountain areas rich in feature information, but with little salient geometric information. When the rewarded corner was directly adjacent to the feature corner, the chickadees did not encode the overall shape of the enclosure. When the rewarded corner was at an all-white corner, chickadees were able to use the geometric information. On conflict tests, chickadees that had been trained to go to the feature adjacent to the food focused their search on almost every trial at the featurally correct but geometrically incorrect corner. In contrast, the chickadees who were trained to find food across from the feature wall divided their searches evenly between the featurally and geometrically correct corners. Therefore, the use of geometric information was not a dominant strategy for mountain chickadees. Recently, the same research group has addressed part of this question by comparing laboratory reared black-capped chickadees, wild-caught black-capped chickadees, and wild-caught mountain chickadees (Batty et al., 2009). For the black-capped chickadees, there were no differences between the two groups. The wild-caught mountain chickadees relied less on geometric information than either rearing groups (hand-reared or wild-caught) of black-capped chickadees.

While these results are tantalizing, it remains uncertain if the differences were because of the species or the rearing environment, as wild-caught and laboratory reared mountain

chickadees were not compared. In a controlled laboratory environment, using a different species, Brown, Spetch, and Hurd (2007) altered the rearing environment of fish (*Convict cichlids*). Half of the fry were raised in uniform white circular tanks lacking unique geometric information. The others were raised in white rectangular tanks where geometric information was salient. After 4 months in these environments, half of the fish in each rearing group were trained in either an all-white geometry condition or a rectangle with a blue feature wall adjacent to the correct corner. The circular-reared fish learned the feature training task faster than the geometrically reared fish. When feature and geometric information was placed in conflict, the circular-reared fish selected the featurally correct corner, while the rectangle-reared fish selected a geometrically correct corner. This supports the idea that early experiences can augment feature use for reorientation, contrary to modularity theory, and appears to reweight the hierarchy of orientation cues, in support of adaptive combination theory.

Vallortigara et al. (2009) have critiqued one aspect of the fish rearing study. They propose that as the fish were reared for the long period of time in groups of fish, that the experimenters may have “directly exposed the experimental fish to geometrical and featural information as visible on conspecifics’ bodies, and in particular favored using the individual conspecifics’ location as cues for spatial orientation and navigation” (p. 22). However, there are a few reasons why this is an unlikely concern. Fish in both conditions were reared in the same types of groups, and therefore the differences in behavior are unlikely to arise out of the rearing dynamics. Second, although there are markings on the fish, which can contribute to normal visual system development, it is not clear how markings on the body of the conspecifics might contribute to reorientation performance, because the fish are moving in the enclosures, and thus are not stable reference points either for orientation or navigation.

The critics of the fish study have conducted their own rearing studies with chicks. Chiandetti and Vallortigara (2008) raised all male chicks for 3 days in either circular or rectangular enclosures. Over the next 3 days, chicks were trained to find food in a rectangular apparatus that was either uniformly white or had a unique feature panel at each corner. During training, both groups of chicks made geometric errors and they required the same number of trials to learn the task. Additionally, when the feature panels were removed, chicks spontaneously encoded the geometry of the enclosure irrespective of rearing condition. Thus, for chicks, the early rearing environment does not seem to influence reorientation, in contrast to the more flexible system of fish. However, the rearing studies with fish and chicks differ in several ways. The fish were raised in distinctive environments for a much longer period of time than the chicks. Additionally, fish have an extended juvenile period, which may support cognitive flexibility.

Recently, Twyman et al. (2009) conducted a rearing study with a mammalian species—the mouse. Mice were housed in either circular environments (which were featurally enriched) or rectangular environments (which were geometrically enriched). Young mice that were housed in the circular environment were faster to learn to use features during training. In contrast, young mice that were housed in the rectangular environment were more accurate using geometric information when it was not explicitly required for the task (i.e., when the feature panels were removed from the training rectangle). Thus, for young mice, the rearing environment alters the use of feature and geometric cues for spatial reorientation. As an extra

component of this study, the plasticity of adult and juvenile mice was compared. Interestingly, adult mice retained some plasticity. The rectangular housed adult mice retained the advantage using geometric cues. In contrast, the circular housed adult mice did not outperform their rectangular adult mice counterparts on tests of feature cue use. Thus, for mice, experience plays an important factor, particularly during the juvenile period, but also for mature participants. Thus, initial studies indicate that mice, convict cichlids, and mountain chickadees seem to display larger rearing effects than domestic chicks or black-capped chickadees.

5.3. Summary

Experience matters. In the first section, we reviewed evidence that short-term training experience alters the relative use of feature and geometric information for human adults, children, and pigeons. Each of the experiments is important for different reasons, from the modularity or core knowledge positions. First, since pigeons were studied, it is unlikely that language training is the catalyst for feature use. However, the rebuttal of the modularity position is that the extensive training required for nonhuman animals is not on par with the fluid reorientation system of humans. Thus, the short-term training experiments demonstrate that with quite limited exposure, adults and children's reorientation strategies are altered by experience. In the second half of this point, it was demonstrated that experience also matter over long-term rearing studies, for mountain chickadees, fish, and mice. These experiments are problematic for the innate endowment positions of modularity and core knowledge theory. Next, we turn to a recent reformulation of the geometric module hypothesis.

6. Reason 4: Features are used for true reorientation

We have offered three reasons so far to doubt the existence of a geometric module, by refuting the unique role of language, by demonstrating that modularity theory is too rigid to be able to explain variable phenomena, and by refuting the innate endowment claim through demonstration that experience alters reorientation. There is a recent rebuttal, however, that attempts to rescue the geometric modularity proposal by advocating a two-step account in which feature use is merely associative. We review evidence that contradicts this claim and that demonstrates that features can be used for true reorientation.

6.1. The two-step model

Lee, Shusterman, and Spelke (2006) suggest that there are two separable systems of spatial processing and that only the geometric system is used for reorientation per se. Features can be used, but not for reorientation. They can only be used as beacons (as direct markers of a goal location). To support this argument, they disoriented 4-year-old children in an all-white circular space containing three hiding containers arranged as an equilateral triangle. One of the containers had a distinctive color and shape. Although children could find objects hidden in the distinctive container, they failed to use it to choose between the two other

identical containers. Based on this finding, Lee et al. argue that “search behavior following disorientation depends on two distinct processes: a modular reorientation process...and an associative process that directly links landmarks to locations” (p. 581).

It might be argued that prior data already contradict the two-stage associative account. Specifically, recall that Learmonth et al. (2001) showed that children’s search for an object hidden in an all-white corner of a rectangle with one blue wall was as good as their search for an object hidden in the blue-and-white corner; it may seem initially that the all-white corner provides no associative cue for such performance. However, that characterization is not correct in the two-step account. In a rectangular room, there is only *one* all-white corner that is geometrically correct, so “all whiteness” marks the corner as distinct from the geometrically correct alternative as much as the “blue and whiteness” marks the other geometrically congruent corner as correct. In fact, “all white” is used as one of the pieces of encoded information in a recent associative model of the reorientation task (Miller & Shettleworth, 2007). Lee et al. would clearly argue that reorientation of the kind at stake in the geometric module debate implies that people can use a feature to choose correctly among *more than one* all-white corners with the same geometric characteristics. Testing this hypothesis would require the use of an enclosure with more than four sides.

6.2. Evidence against the two-step model

One reason that Lee et al. may have failed to find that 4-year-olds use features to reorient may be the fact that the feature they used was extremely proximal to the layout (in fact, was part of it) and that the feature was obviously moveable. As we have seen, distal landmarks are known to be more useful than proximal ones for spatial functioning in general and reorientation in particular (Learmonth et al., 2008; Nadel & Hupbach, 2006). In addition, moveable landmarks are less likely to be used to guide spatial search than landmarks that are larger and apparently unlikely to move (Gouteux, Thinus-Blanc, & Vauclair, 2001; Presson & Montello, 1988). Thus, the two-step model of reorientation—with geometry guiding true reorientation, and then features as direct markers of a goal location (i.e., a beacon)—seemed possible.

Newcombe, Ratliff, Shallcross, and Twyman (2009) addressed the issue of whether larger and more distal features can be used for true reorientation, using two approaches. The first step was to use an enclosed octagonal search space with alternating short and long all-white walls. The use of the octagon is interesting for a few reasons. Not only is the geometry more complex than that generally used (obtuse angles, and more potential hiding locations), but it is radial symmetric and therefore lacks a single principle axis of space. Recently, Cheng and Gallistel (2005) have proposed that geometry is used for reorientation by encoding the principle axis of space, and then maintaining the correct left-right position along this line.

In Newcombe et al.’s first experiment, 2- and 3-year-old children were able to select a geometrically correct corner in an octagon 70% of the time, significantly greater than chance of 50% (as there are four geometrically correct, and four geometrically incorrect corners). Thus, young children were able to use geometry for reorientation in spaces lacking a single principle axis of space, and therefore reorientation does not seem to solely depend on

the encoding of the principal axis of the shape of the search area. In a second experiment, a feature wall was added to the octagon search space. For this experiment, 3- and 5-year-old children were studied, spanning the age of the children (4 years) in the Lee et al. (2006) study. By adding a feature wall, there is now one geometrically correct corner directly adjacent to the feature wall—and this location can be solved with a beacon strategy. However, there are three other geometrically correct corners that are all white. At these corners, if children are able to use the feature wall, then they must process the feature wall as a landmark, an indirect use of the feature, to successfully reorient. The Lee et al. two-step account predicts that children would first reorient based on the overall geometry of the space, narrowing the search down to the four geometrically equivalent corners. Next, the two-step account predicts that children will successfully search at the beacon target corner, but crucially not at the landmark search corners. With the feature wall present, children were still able to successfully reorient with the geometry of the space, which is explainable by both the two-step and a unified account of reorientation. The crucial comparison is for search at the beacon (adjacent to red) and the landmark (three all-white, geometrically equivalent corners). In the beacon condition, all children performed above chance, which is predicted by the two-step account. In the landmark conditions, all children performed above chance, which is unexplainable with the two-step account to reorientation. Additionally, the 5-year-old children were better (68%) than the 3-year-old children (35%) using the feature as a beacon. This finding is quite difficult for the two-step account. Not only are young children using features as landmarks, but it seems that the beacon system is emerging later in development than the landmark system.

Now that indirect feature use has been demonstrated in the presence of geometric information, the reorientation ability of children was also examined in the absence of geometry (Newcombe et al., 2009; Experiment 3). This experiment was interesting for two reasons. The first is to ask whether the presence of useful geometric information is required for children to be able to use features to reorient. In other words, is geometry required as a catalyst, or can the reorientation system be activated exclusively with feature cues? Second, the triangle array is the closest comparison to the experimental design of Lee et al. (2006). To maintain as tight of a comparison as possible with Lee et al.'s study, 4-year-old children participated in this experiment. In the first portion of the experiment, children were asked to search within an equilateral triangle search array. In the Lee et al. study, the landmark was a uniquely shaped and colored hiding location. In the Newcombe et al. study, all of the hiding locations were identical, and the landmark was displayed on the perimeter of the search space (a circular space made out of a uniformly white curtain). Lee et al. found that children were able to use the feature cue as a beacon, but not as a landmark. In contrast, when the feature was positioned on the wall, the feature was used as a landmark in Newcombe et al.'s study. However, it is possible that the 4-year-old children were able to infer geometry between the three hiding locations and the feature curtain hanging on the circular wall. To rule out this possibility, the feature served as one point of the equilateral triangle, and then children were asked to search between two containers (composing the rest of the triangle) equidistant from the feature wall. The two-step associative account predicts that children should search equally often at each of the hiding locations. However, 4-year-old children

were able to focus search on the correct hiding location. Thus, indirect feature use is successful in both the presence and absence of geometric information, refuting the two-step modular account.

6.3. Summary

A recent revised modular, two-step account has been proposed for reorientation (Lee et al., 2006). In the first step, disoriented participants reorient with the geometry of the space. In the next step, participants can use features only as beacons to home in on a goal location, but crucially, features cannot be used as landmarks for orientation. In contrast to this hypothesis, we presented data that with stable features, children are able to use features as landmarks. Additionally, the presence of geometric information is not required to activate the reorientation system. Hence, early reorientation is not modular, at least not in the sense of Fodor (1983), in contradiction to the arguments of Lee et al. (2006) and the core knowledge position (Spelke, 2008).

7. Reason 5: What exactly is the nature of geometric information?

In reason 5, we question what is meant by geometric information. It is implied in the term *geometric module* that any type of geometric cue should be able to support reorientation. However, we will first demonstrate that not all geometric cues are created equal. Next, we will turn to the specificity of the geometric module. Modularity and core knowledge theorists have claimed that the geometric module is dedicated to the reorientation task, and geometry has certainly been demonstrated to be important for reorientation. However, the modularity position must also demonstrate that the geometry findings cannot be explained by a more general cognitive skill, as this would imply that the system is not specifically dedicated for reorientation.

7.1. Not all kinds of geometry are used early in development

Traditionally, the first type of geometric information to be studied was relative length—alternating short and long walls. However, there are conditions under which relative length can be difficult to use. In a recent study, 4-year-old children were asked to reorient with variations of the height and continuity of geometric information (Lee & Spelke, 2008). In one condition, children were asked to reorient with a rectangular array of four large, stable columns. Children did not use the geometric information that was suggested by the rectangular shape. The experimenters next outlined a rectangle on the floor with tape. Thus, the shape was clear and uniform, but did not have elevation. Again, for this condition, the children did not use the geometric information. Finally, when elevation was added, with either 12-inch or 35-inch-tall walls, children were able to use geometric information for reorientation, with no difference in accuracy depending on wall height. It may be surprising that the taller walls did not increase geometric responding, as the taller walls ought to be

more salient than the low walls. However, what might be important is the presence of any elevation at all. Elevation is required to activate boundary vector cell firing (Solstad, Boccara, Kropff, Moser, & Moser, 2008), and this may have a role to play in the reorientation task. The role of elevation is still ambiguous, however, as is whether geometry can be imputed from separated landmarks (an ambiguity noted by Cheng & Newcombe, 2005). Lew, Gibbons, Murphy, and Bremmer (2009) found that 2-year-old children could reorient using the geometry of the search space for both enclosed spaces and using the imputed geometry from an array of landmarks. In this experiment, the reorientation performance of toddlers was not better for the enclosed spaces compared to geometric conditions that were defined by uniform landmark arrays.

The Lew et al. (2009) experiment further provides evidence against the geometric module hypothesis, by showing how the phenomena may be limited to situations unlikely to occur in natural ecology. Toddlers were asked to reorient in regular rectangular or isosceles triangle conditions and, as would be expected, performed above chance in these conditions. Importantly, however, toddlers were next examined in *irregular* quadrilateral and *irregular* triangular environments. The irregular environments are interesting because they contain unique geometric information, including unique corner angles and relative wall length differences, but disrupt the symmetry of the space. Toddlers' choices fell to chance levels in the irregular conditions. Thus, even when corner angle and unique lengths are present, there are some conditions when toddlers fail to reorient using geometric information. This finding is problematic for the geometric module hypothesis, because the geometry that is found in the natural environment is much more likely to resemble the irregular configuration (where toddlers fail to use geometry) than the symmetric search spaces that have been traditionally used to study this process (Lew et al., 2009). There are clearly variations in the likelihood of use of various kinds of relative length cues for reorientation. Because the natural environment does not contain unambiguous enclosures whose geometry is defined by continuous elevations, the generality of the geometric module approach seems uncertain.

Geometry also includes more than simply the length and relative positions of lines and extended surfaces—angles are geometric. The original studies of the geometric module mainly used rectangles in which all walls met at 90 degree angles. Hupbach and Nadel (2005) asked whether children could use the angular information in a rhombus to recover from disorientation. As shown in Fig. 3, a rhombus has four sides of equal length, with two



Fig. 3. The rhombus enclosure. Each of the sides of the enclosure is equal in length. Therefore, the only unique geometric information available in these enclosures is that of corner angle. There are two acute (A) and two obtuse (O) angles in each corner. When there is no additional information, the best that the disoriented child can do is to divide search between the two corners with identical angles, as in the first rhombus. However, when a feature wall is added, as in the second rhombus, then it is possible for participants to use the feature wall to disambiguate the two equal angle corners (O_F from O or A_F from A). From Hupbach and Nadel's (2005) study, children start using the angle information as well as the feature information at 4 years of age.

equal obtuse angles and two equal acute angles. Reorientation analogous to that achieved in rectangular rooms would involve children concentrating search on the two angles that correspond to the corner in which they saw something hidden. However, although children as young as 18 months use wall-length information successfully (Hermer & Spelke, 1996), children did not succeed in using angular information until the age of 4 years. And, by the time they were using this kind of geometric information, they were also using a feature to choose successfully between the two corners. It is hard to see how an ability can be characterized as “geometric” if it does not include information about angle. Next we turn to the claim of specificity.

7.2. Use of scalar and nonscalar cues by toddlers

Recently, Huttenlocher and Lourenco (2007) have questioned the geometric module on the grounds of specificity. It has been demonstrated that geometry can be used for reorientation when it is available. However, if there is a dedicated geometry system that is dedicated only for reorientation, then it must also be demonstrated that reorientation fails in the absence of geometric information. As we review below, toddlers can succeed in square environments that lack unique geometric information. As an alternative, Huttenlocher and Lourenco (2007) proposed that the reorientation behavior can be explained by a more general ability to discriminate and compare scalar (or relative) cues. The lengths of walls define a continuum of size, a scalar comparison. By contrast, colored versus white walls define contrasting categories and are nonscalar. It might be that scalar cues are easier to use for reorientation than nonscalar ones. This contrast would be more general than (and different from) the contrast between geometric information and features. To test this idea, Huttenlocher and Lourenco (2007) tested 18- to 24-month-old children in square enclosures. The toddlers were shown the hiding location of a toy and then were disoriented before being allowed to search for the toy. Since the square provides no unique geometric information, the modularity position predicts a failure of reorientation. However, with small and large polka dot patterns, as shown in Fig. 4, the toddlers were able to successfully pick the target

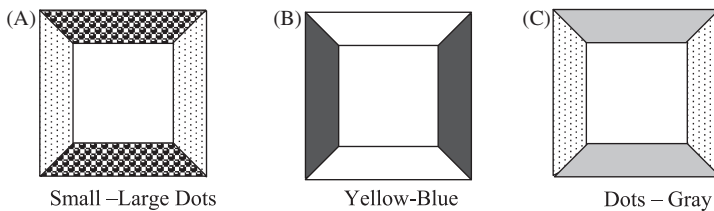


Fig. 4. Enclosures to test the use of scalar (A) and nonscalar cues (B,C) in the absence of geometric information. As we can see in this figure, the diagonal corners are identical to each other. For example, in panel (A), the small dots are to the left and the large dots to the right in both the top left and the bottom right corners. Thus, choices to either of these corners are scored as correct, and hence performance is compared to 50% chance. In panel (B), the walls appear to be black and white. In the actual experiment, the walls were either blue and red for children, or blue and yellow for mice (as mice cannot perceive the color red).

corner about 70% of the time, significantly above chance levels of 50%. When the adjacent walls were defined by nonscalar cues, either alternating blue and red walls or walls with dots alternating with gray walls, the toddlers were unable to reorient at above 50% chance levels. As there are four potential hiding locations, one might expect chance to be 25%. However, there are two equivalent corners that preserve the relationship between dot size and left-right position (e.g., large dots on the left). Thus, the two equivalent corners are scored as correct and search performance is compared to 50% chance.

There are two possible explanations for why toddlers were able to reorient in the scalar cue condition and were unsuccessful in the nonscalar cue conditions. Ordinal relationships may be more readily mapped onto spatial position than the other two cues. Alternatively, the small-large comparison has multiple co-occurring cues such as size, spatial density, and the number of dots per wall while the other conditions have only one cue. Lourenco, Addy, and Huttenlocher (2009) explored the latter possibility by comparing reorientation with a single dimension to that with a compounded dimension. When adjacent walls differed in luminance, reorientation was slightly but reliably above chance (59%). When adjacent walls differed in a single way, namely solely orientation of lines, reorientation was somewhat lower and not significantly above chance (55%). When the two were combined, reorientation was more successful than with either cue alone, and toddlers were able to find the toy on the first search about 70% of the time. However, although the luminance effect is small, the importance of scalar cues is underlined by findings from an additional composite-cue condition. While composite cues help, at least one of the cues must be relative in order to get a boost in performance. When two categorical cues were combined (red Xs and blue Os), reorientation was still at chance.

Categorical cues may not be absolutely impossible to use, but just more difficult. Working with 18- to 24-month-old children in square enclosures, Nardini, Atkinson, and Burgess (2008) found that children were able to reorient using a nonrelative cue, alternating blue and white walls. However, performance was far from perfect, at 61% accuracy. Toddlers may have performed slightly better in this experiment than in Huttenlocher and Lourenco's for several reasons. First, the size of the enclosure was nearly three times larger. From Learmonth et al.'s (2001, 2002) work, we know that features are easier for children, and adults and nonhuman species for that matter, to use in larger spaces. Additionally, toddlers participated in up to eight trials (compared to four) and we know that practice augments feature use (Learmonth et al., 2008; Twyman et al., 2007). In fact, if only the first four trials are analyzed for Nardini et al.'s experiment, then reorientation is only marginally significant with a two-tailed test. Interestingly, the distinction between right and left sense appears to already be developing in the 18–24-month age range. In one of the conditions of Nardini et al.'s experiment, the opposing walls were covered with animals. In the symmetric condition, the animals were arranged in a mirror image fashion so that the toddler would have to combine the feature information with the left-right distinction in order to focus search on the correct corner. For example, the target corner may have been adjacent to a lion. However, there would be a lion in each of the four corners, so the toddler was required to remember that it was the lion on the left that marked the goal location. In the asymmetric condition, the animals were identical at the two diagonal corners, but different on the

opposite diagonal. So the target corner may be adjacent to the lion on the left, but now there is a flamingo on the right so the toddler no longer needs to make the left-right distinction for reorientation. It is interesting to note that the toddlers searched above chance when the left-right distinction was required for successful performance, but removing the sense requirement boosted the toddlers' performance to 73%, close to the performance seen with small and large dots, when the left-right judgment was not required of children in the reorientation task.

7.3. Use of scalar and nonscalar cues by mice

Mice as well as human children show a greater ability to use scalar (as opposed to nonscalar) information to reorient, showing that the advantage of scalar information is not due to symbolic or linguistic ability. In addition, the data from mice make clear that nonscalar information *can* be used to reorient, albeit with somewhat greater difficulty than scalar information, as was hinted at in the data from human children. These conclusions come from a study based on Huttenlocher and Lourenco's (2007) study, in which C57/BL/6 mice were trained to find a food reward in the same conditions (Twyman, Newcombe, & Gould, 2009). Additionally, the extra trials that can be collected from mice compared to toddlers allowed a closer look at the ability to use nonscalar information for reorientation. The mice were able to reorient using scalar information (12 trials) much faster than when offered either the nonscalar color (38 trials) or dots-gray (33 trials) comparisons. This difference in acquisition time for the different types of feature is difficult for the modularity position to explain as there is no difference in the geometric information available across groups.³ Furthermore, this experiment reconciles the seeming discrepancy between Huttenlocher and Lourenco (2007) and Nardini et al. (2008) by demonstrating that nonscalar cues can in fact be used for reorientation, provided there is sufficient time for learning.

The common thread across all of these experiments with toddlers in square enclosures is that in some cases they are able to successfully reorient in the absence of geometric information, contrary to the predictions of a geometric module. Scalar information is preferred. The finding that nonscalar information can be used in a square enclosure, but is harder to use than scalar information, is confirmed in studies with mice. Local view theory, which entails matching a snapshot of the to-be-remembered location with the current view, would be able to explain Nardini et al.'s (2008) results. However, proponents of modularity theory are not likely to subscribe to local view theory, in the manner it is being discussed in the literature, as this position is explicitly nonmodular (Cheung, Sturzl, Zeil, & Cheng, 2008; Sturzl, Cheung, Cheng, & Zeil, 2008).

7.4. How does the vertical axis fit in?

In just about all of the experiments reviewed, reorientation has been examined on a horizontal surface. For people, the majority of our navigation occurs on the horizontal plane, although there are notable exceptions when traveling up or downhill. However, other species, such as marine species or animals that can fly, may spend much more time navigating

in both the horizontal and vertical plane. This vertical aspect of navigation has recently been examined with the reorientation paradigm (Nardi & Bingman, 2009). In this task, pigeons were asked to reorient in an isosceles trapezoid arena. When the ground was flat, pigeons were able to learn the task. When the ground was sloped, pigeons were faster to learn the task and more accurate. How should slope be classified in terms of a reorientation cue? The two main classes of cues that have been studied with the reorientation task are geometric and feature cues. However, slope does not appear to fit easily into the classification of a geometric or a feature cue. Thus, information along the vertical axis, namely slope, appears to be a salient reorientation cue that may warrant its own category of cue type.

7.5. Summary

The data reviewed in this section make the point that the dichotomy between use of geometry to reorient (obligatory and early) versus use of features (variable, late, and dependent on language) is overly stark. First, relative length is only used with continuous enclosures defined by raised barriers, which poses problems for how useful the geometric module would be in natural ecology. Second, one kind of geometry, angular information, is not used until fairly late in development. Once it is used, features are used as well. Third, features can be used to reorient in square rooms, especially with scalar information but likely with nonscalar information as well. Fourth, a salient cue in the natural world—slope—is important in reorientation and seems to constitute an additional class of information that does not fit neatly into the geometry versus feature dichotomy. Overall, in reason 5, we question what is meant by geometric information.

8. Summary of the five reasons to doubt the geometric module

Here, we have outlined five reasons and evidence to doubt the existence of a dedicated geometric module for reorientation. There were many reasons to doubt that language played a unique role in the integration of feature and geometric information, based on evidence that nonhuman animals flexibly used geometric and feature cues for reorientation, and that human's reorientation ability was not dependent solely on language. Next, variable phenomena were reviewed and it was demonstrated that modularity theory and core knowledge positions do not have enough flexibility in their theoretical accounts of reorientation to be able to explain these variable phenomena. For example, geometric and feature cue use depended on environment size, and the presence or absence of overshadowing, blocking, and potentiation effects were not explained by modularity theory. Additionally, both modularity and core knowledge postulate that the reorientation system is innate, and thus experience should not influence the behavior of reorienting organisms. We demonstrated that experience, through short-term training experiments and over the long-term with rearing experiments, had an influence on the orientation performance of participants. Next, a recent two-step modular model of reorientation was outlined. Advocates of the core knowledge position argue that geometric information is first used, and solely used, for reorientation. Subsequently, features

are used associatively to pinpoint a goal location, but crucially features cannot be used for reorientation. In contrast, we reviewed evidence that features can be used for true reorientation, both in the presence and absence of geometric information. Finally, we discussed what types of geometric information can be used across development, and across species for reorientation. It has become apparent, that not all types of geometry are used for reorientation, and a more specific definition of geometric information may be required. For all of these reasons, discussed more thoroughly above, there are many limitations to modularity and core knowledge theory. In the next section, we will review more recent theories that attempt to explain the reorientation phenomena, as summarized in Table 3.

9. Alternatives to modularity

The first part of this paper offered five reasons to doubt the existence of a geometric module. In the next section, we change our focus to review recent alternative theoretical models. We evaluate each of them using the score card of whether it could account for the phenomena shown in Table 3, which are quite well established and in Table 4, phenomena that are less clear and need further exploration. We emphasize the criterion of whether the model

Table 3
Phenomena to be explained by any model of reorientation

Phenomena
1. Reorientation using relative length is easier than reorientation using angle size.
2. Reorientation relies more on features and less on geometry as enclosure sizes become larger.
3. Features are more likely to be used as children get older, but the improvement is continuous in larger rooms whereas, in smaller rooms, features are not used spontaneously until 6 years of age.
4. Feature use is enhanced by language training.
5. Feature use is enhanced by prior experience with features in a variety of situations.
6. Feature use is attenuated by both language interference and spatial interference.
7. Scalar information is easier to use for reorientation than nonscalar information.
8. Overshadowing and blocking are sometimes but not always observed with featural and geometric information—and potentiation is even possible.
9. Distal feature cues are used at a younger age than proximal feature cues.
10. Movement enhances the integration of feature and geometric cues.

Table 4
Phenomena that require clarification and further experimentation

Unclear Phenomena
1. Is geometry more likely to predominate over features in a working memory task as opposed to a reference memory task?
2. Is geometry harder to use when it must be imputed from separated points rather than being instantiated by continuous surfaces?
3. Why are direct features sometimes (but not always) easier to use than indirect features in search after disorientation?

could account for development in general, as well as for the specific developmental facts, such as the use of length before the use of angle or the use of features in large but not small spaces from an early age.

9.1. Adaptive combination

Adaptive combination was introduced by Newcombe and Huttenlocher (2006) as a theory whereby multiple sources of spatial information are integrated into a nonmodular and unified representation. It is one version of a number of models of spatial functioning that postulate the weighted integration of a variety of relevant sources of information to support spatial functioning (Cheng, Shettleworth, Huttenlocher, & Rieser, 2007). Information that is high in salience, reliability, familiarity, and certainty, and low in variability, is given priority over other sources of information. Unlike modularity, the adaptive combination model suggests that this information is continually being modified by the creatures' experience. Cues that lead to adaptive behavior are elevated in the probability of their use, by increasing the relative weights of that information source, and cues that led to maladaptive behavior are decreased in weight. In terms of development, interaction with and feedback from the environment allows the evolution of relative weights for the potential sources of information that are increasingly well adapted.

Adaptive combination offers an explanation of many of the facts outlined in Table 3. Points 2, 5, 6, and 7 were predicted by adaptive combination theory and then empirically tested. Point 2 was predicted by adaptive combination theory since as the size of the enclosure increases, there are several reasons to expect that the use of features would increase: First, the size of the feature wall is larger in the larger spaces, and therefore is more salient; second, movements around the feature wall create less variability in the large space than the smaller enclosures. Points 5 and 6 are related to each other as both involve either enhancing feature use through training and experience or decreasing feature use through interference tasks. Adaptive combination predicts that practice either directly with the features (or through language training—Point 4) will increase feature use as this experience increases the cue weightings of features relative to geometry. Because there is no reason to think that features are only encoded verbally, adaptive combination predicts that interference tasks with either verbal or spatial encoding will be detrimental to performance, although not fatal as there are back-up systems of encoding that will still enable partially successful performance. Finally, in terms of point 7, scalar information is potentially easier to use than nonscalar information for two reasons. The less interesting explanation is that scalar information, as it was studied, contained more potentially useful cues (size, number, density) than the nonscalar comparison. The more interesting possibility is that scalar cues may be more readily mapped onto spatial position than nonscalar cues.

Point 1 can also be explained by adaptive combination theory, although arguably in a post hoc fashion. Relative length may be easier for children to use than corner angle because of differences in memory demands between the two types of cues. When facing a corner, especially in small rooms, the small and large walls intersect at the corner right in front of the child. This facilitates a comparison of relative length. For corner angle in contrast, the child

who is facing the correct corner must rotate to compare the current corner angle to the other corners where memory demands may increase the difficulty of using corner angle over wall length as a reorientation cue.

Adaptive combination is an overarching theoretical perspective that argues for an active and adaptive use of relevant information to support spatial reorientation. Recently, other research teams have proposed more specific models. These models can be seen as compatible with the general principles of adaptive combination theory, and they have tested some of the specific reorientation phenomena listed in Table 3. We turn now to those models.

9.2. Operant model using Rescorla-Wagner principles

Miller and Shettleworth (2007) proposed a model of reorientation based on Rescorla and Wagner's (1972) principles of association. However, the Rescorla-Wagner model applies to classical conditioning, so Miller and Shettleworth revised the model to apply to an operant situation because, after disorientation, the animal chooses the corner to approach and therefore selects for itself the stimuli experienced during the experiment. Thus, the model includes a measure of the probability of encountering each corner, based on the associative strengths of all of the cues at each corner.

This model had as its central goal to provide a unified account of the blocking, overshadowing, and potentiation effects discussed earlier in the article. One of the key concepts of the model is feature enhancement. If the organism learns the geometry of the environment, then this cue leads to reward half of the time. However, a key assumption of the model is that the creature quickly learns to select the correct corner on the basis of feature information. Since the correct geometric information is paired with the reward quite frequently, the feature is aiding the creature to learn about the geometry of the space. Then, because the organism has overvalued the contingency of the geometric cue to greater than 50%, the organism starts making rotational errors and eventually the organism learns the actual contingency of reward for geometric information.

As for the more general adaptive combination theory, this approach is a nonmodular model. The transitory nature of feature enhancement can explain the mixed results with overshadowing and blocking effects depending on what point in training the test trials were administered. This operant model is able to explain many of the reorientation findings, including the original Cheng (1986) experiments and the blocking, overshadowing, and facilitation effects of Pearce and colleagues. Additionally, a recent revision of Miller and Shettleworth's (2007) model is able to account for the room size effects for children, fish, chicks, and pigeons.

Recently, there has been a critique of this model (Dawson, Kelly, Spetch, & Dupuis, 2008). Although the authors agree with the fundamental premise that reorientation is an operant learning task, they point out that Miller and Shettleworth's formula for probabilities is based on associative strengths, which can be positive or negative. Thus, the mathematical equation sometimes produces impossible probabilities of less than 0% or greater than 100%. As a solution, the authors provide an alternative engine, a perceptron, to drive the mathematical side of the model while keeping the operant vision for reorientation. A perceptron is

an artificial neural network that has inputs that encode stimuli, outputs that respond to stimuli, and flexible weighted connections between the inputs and outputs. Thus, the perceptron is still based upon associative weights, but the probabilities remain between 0% and 100% and the operant nature of the task is preserved. The Dawson et al. article arguably represents a friendly amendment to the Miller and Shettleworth approach. Miller and Shettleworth (2008) took the opportunity to reply to Dawson et al. They agreed that there was a flaw in one of the calculations and have modified the equation to eliminate aberrant probabilities. This modification has again demonstrated “how what appeared to be exceptional kind of cue interactions in geometry learning experiments can arise from an unexceptional competition for learning among geometric and other cues” (p. 422).

How then does the model fare in explaining the phenomena listed in Table 3? One issue is that, although the Miller (2009) model tackled age effects, it does so simply by adjusting parameters in the model to create age differences. There is no independent motivation for why such parameters might be age graded. The model also has yet to address phenomenon 1 (angle size is harder to use than wall length), some aspects of phenomenon 5 (training and malleability), phenomenon 6 (interference effects), or phenomenon 7 (scalar information is easier to use than nonscalar). Phenomena 1 and 7 could be tackled by adjusting parameters, but as with the treatment of age, it could be argued that such adjustments are ad hoc. Some aspects of Phenomenon 5 are very naturally explained by the model, which after all is an operant model, but it is not clear that the model could cover the more abstract generalization of the training studies of Twyman et al. (2007). However, this model is an excellent start, and it will be interesting to see the model refined to be able to explain more of the phenomena listed in Tables 3 and 4.

9.3. *Local view theory*

Because of accumulating evidence against modularity, in particular the findings of Pearce and colleagues, Cheng (2008) is now quite skeptical that there is a geometric module. In its place, Cheng predicts that either a version of Miller and Shettleworth's (2007) operant model or local view theory will take its place. Local view theory has grown out of the research on insect navigation, which is largely accomplished by matching a stored retinal image to the current image. When applied to the reorientation task, local view theory postulates that rotational errors arise out of the image-matching process (Cheung et al., 2008; Sturzl et al., 2008). To explain the original Cheng (1986) finding that rotational errors are made by rats in rectangular enclosures, this nonmodular account suggests that the organism stores an image of the target location. Once disoriented and released, the organism looks around and then moves in the direction that minimizes the discrepancy between the stored and the current image. The process is repeated until the organism arrives at the end point. It is a nonmodular account because geometric cues are not given a privileged status. Local view theory circumvents the issue of what should be counted as a feature and what should be considered geometry by assigning equal status to all possible cues. From this perspective, geometric and feature information are stored together in the target corner image.

How do rotational errors arise if all of the pertinent information is available to home in on the correct corner? The authors propose that the target image is segmented into information at the edges of the enclosure and internal information of the walls. Furthermore, the saliencies of the edges and internal information may be equal, or one may be stronger than the other. The model predicts that when the edges are more salient, then the agent will make more rotational errors. However, if the internal information is enhanced, then the agent will go towards the correct corner.

To test this theory, the authors simulated the reorientation paradigm using virtual reality simulations and a robot that stored the target image and then moved along the image difference function (minimizing the difference between the current and stored panoramic image) to determine view whether based matching would result in rotational errors. When the rectangular arena was all black, either with or without feature panels, the robot ended up in either the correct or the rotationally equivalent corner. A similar result was found with three black walls and one white feature wall. Furthermore, the authors were able to demonstrate that increasing the salience of the internal information reduced rotational errors and vice versa. Thus, the authors demonstrated that the rotational errors from Cheng's original experiment do not require a modular account of reorientation.

After demonstrating that rotational errors can arise in view-based matching in rectangular spaces, the authors tackle kite-shaped spaces (Graham et al., 2006; Pearce, Graham, Good, Jones, & McGregor, 2004). They selected these experiments as they deemed them particularly problematic for modularity theory. In one of these experiments, the rats were searching for the platform in a kite-shaped enclosure. When the wall color changed from trial to trial, it should have been very easy for the rats to depend on geometric information. In contrast, this was a very hard task for the rats to learn; in fact, a facilitation effect was found since making the feature wall stable enhanced learning of the geometric information. When the robot was put to the test, local view modeling performed well, with a few minor exceptions.

The hypothesis of an image-matching mechanism that produces rotational errors is gaining momentum. In a similar vein to the robot modeling just discussed, a different group of authors has modeled some of the reorientation data with computational models of rats (Sheynikhovich, Chavarriaga, Strösslin, Arleo, & Gerstner, 2009). A computational neural model was developed that had both an egocentric stimulus-response strategy as well as an allocentric place-based navigation strategy. One interesting point of this model was that the allocentric strategy arose out of the combined input of visual snapshots, path integration, place cells, and grid cells. When this simulated model was tested in different conditions, the authors also found that rotationally equivalent errors arose in the allocentric conditions, even though the underlying representation was nonmodular. Thus, for both the robotic as well as the computational neural model, it is at least possible, in theory, for rotational errors to arise out of a unified cognitive representation as an artifact of an image-matching process.

A recent study with children is one of the first attempts to test an image-matching approach with children (Nardini, Thomas, Knowland, Braddick, & Atkinson, 2009). In this study, children were disoriented and then were asked to retrieve a hidden toy either from a position that facilitated image matching (i.e., could be encoded in a viewpoint-dependent

manner such as left of the feature wall) or from a novel position that was viewpoint independent, and thus prohibited image matching. Four-year-old children were successful only in the viewpoint-dependent condition. At 5 years of age, children appear to be transitioning from search with a viewpoint-dependent strategy, to a viewpoint-independent strategy. By 6 years of age, children are able to reorient using a viewpoint-independent strategy. Thus, below the age of 6, there is some support that children may be using an image-matching approach to reorientation. However, by 6 years of age, children are able to successfully reorient from novel viewpoints, and thus, it appears that there is an alternative strategy that older children and adults can use for reorientation that seems difficult for local view theory to explain.

There are many attractions to local view theory, including its simplicity, specificity, and testability. As the authors mention, it has yet to be determined how the reference image is acquired in the real world, by specific animals or by people of different ages. In addition, perhaps because the image acquisition problem has not been tackled, we do not know how the model would account for age-related differences in feature use, as well as for the room size effect, training and malleability effects, or differences between scalar and nonscalar information (see points 2, 3, and 5 in Table 1). Perhaps most troubling is the fact that there is evidence that directly challenges the central premise of this approach, that is, that organisms reorient using local views without encoding the overall shape of enclosures. Huttenlocher and Vasilyeva (2003) found that toddlers formed a representation of enclosures shaped like an isosceles triangle that was abstract enough to permit recognition of a corner as the “same” despite large variations in the triangle’s appearance that resulted because the children might be either inside or outside the enclosure after disorientation. They also found that children typically went straight to the correct corner from a variety of initial facing points, without needing to survey the whole enclosure or large parts of it, as would seem to be predicted by the local-view approach.

9.4. Different neural substrates?

Although not yet directly relevant to reorientation, a recent set of studies by Doeller, Burgess, and colleagues provide an elegant approach to studying spatial cognition. They have examined the behavioral and brain bases of landmark and boundary information in goal location tasks when adult males are semioriented (Doeller & Burgess, 2008; Doeller, King, & Burgess, 2008). In an object memory task, participants were introduced to a virtual reality environment where distal cues (mountains, clouds, and a sun) could be used as an orientation cue, but not as a distance cue to the object’s location. Additionally, there was a circular boundary defined by a uniform stone wall, and a local landmark for the object, such as a traffic pylon. Participants were asked to navigate through a sequence of objects while remembering where they found them. Some of the objects were stable relative to the landmark (the pylon) and others stable relative to the boundary (the stone wall). Then participants were serially shown the objects and asked to place each where it should go. They received feedback during the training part of the experiment. To prevent egocentric responding, after an item was found, the screen went blank and participants reappeared at a

new location along the boundary, facing inwards. Thus, participants are prevented from following the same set of body responses to replace the target. However, it is unclear whether participants were fully disoriented in the same manner as the reorientation paradigm.

Behaviorally, the data suggested that the landmark and boundary information were learned in parallel. However, the principles of learning appeared to be fundamentally different for each type of information. The landmark learning followed associative learning principles, as demonstrated by blocking, overshadowing, and learned irrelevance learning. Boundary learning did not show any of these effects and was proposed to be learned incidentally.

To follow up on the behavioral data, an fMRI study was conducted to determine whether there were differences in how the brain processed boundary and landmark cues. The boundary cues activated the right posterior hippocampus while landmark cues activated the right dorsal striatum. The study also suggested how the brain combines these types of information. After parallel processing in independent systems, if only one or the other region predicts behavior, there is no additional activation. However, if the sources of information are in conflict or are both required for adaptive behavior, then the ventromedial prefrontal cortex mediates the combination of information from each system. Thus, in a place-finding task, there appears to be different neural instantiations of each cue type. This type of experimental approach, when applied to the reorientation paradigm, could be a fruitful line of inquiry.

In a complementary study, Bullens et al. (2009) adapted the object memory task for use in a 3-D space to examine the developmental trajectory of landmark and boundary information. In this version, the children entered an enclosed circular search space. The proximal landmark cue was a large traffic cone. Beyond the wall of the enclosure, distal orientation cues were displayed. Between trials, children were disoriented in a similar fashion to the standard orientation paradigm. Perhaps not surprisingly, adults were more accurate locating the target location (84%) than the 5- and 7-year-old children (26%). However, both groups searched in the correct location significantly more often than chance. There were also qualitative differences between the types of searches of adults and children. Adults were more dependent on boundary cues and were more accurate using angular estimates. In contrast, children evenly used boundary and proximal feature cues (albeit more weakly than adults) and were more accurate using distance estimates. No age-related differences in either accuracy or type of search were found. Thus, as the authors point out, it will be interesting to compare both younger and older children on this task to be able to understand which brain systems are developing when, and how cues are reweighted and integrated later in development.

This approach combines behavioral, neural, and developmental data to create a potentially elegant and fruitful model when applied to the traditional reorientation paradigm—which the paradigm used in the research was not. Thus, it not only remains to be seen whether it can explain all the phenomena of Table 3, including development but also whether it can explain the basic phenomena discovered in the original Cheng (1986) research. If it is successful, it may have the interesting implication that it will allow us to have our module and discard it too. That is, the processing of featural and geometric infor-

mation could, possibly, occur initially in two distinct brain areas, and yet, as needed, be combined and weighted in yet another. The way that the reorientation paradigm is conducted, it seems that there are two components to the task, first reorienting, and then navigating to the goal location. There has been quite a bit of research on the second component, navigating to a goal location, which may depend in part on place learning and response learning, which may be supported by the place cells of the hippocampus and the striatum, respectively. An additional layer is added to the reorientation paradigm, namely regaining a sense of direction, which is less well studied. As a start, it seems that the head direction cells, first proposed by Taube (1998) that are found in the Papez's circuit, including the postsubiculum, anterior thalamus, and retrosplenial cortex, would be important components of such a system. It will be interesting to explore the relative contributions of place cells, grid cells, head direction cells, and border cells to the reorientation task.

10. Conclusion

Massive modularity is a popular way to conceptualize human cognitive functioning, and it is attractively simple to explain development by postulating that modules are innately specified. Core knowledge positions share some of the same properties of modularity theory—namely innate endowment, areas of specialization, and characteristic limitations of each system. In contrast to massive modularity, the core knowledge position advocates a small number of modules, on the order of four or five areas of core knowledge. Many invocations of the term *modularity* are so vague as to be essentially untestable. A welcome exception has been the geometric module, which has been precisely defined and operationalized. We believe that the idea, once tested, has been found to be wanting, and that the majority of the empirical evidence is difficult to explain when one postulates modules, either from the massive modularity perspective, or from the core knowledge theory. Recently, the first proponent of the geometric module, Cheng (2008) has reviewed some of the evidence that makes the geometric module hypothesis quite unlikely to be true. What alternative model will take its place is not yet completely clear, but likely it will be an adaptive integrated model similar in spirit to ways of thinking about development suggested by connectionism, dynamic systems theory, and Siegler's (1996) model. Whether these doubts about one example of an innatist-modular account of development will extend to other hypothesized modules, such as theory of mind, cannot of course be stated from the present data. The example of the geometric module does, however, give us reason to be cautious about facile acceptance of the hypotheses of massive modularity or core knowledge and innate specification.

Notes

1. Additionally, the early work with rats was conducted with all male subjects. Rats have been shown to exhibit stable sex differences in spatial learning, unlike mice (Jonasson, 2005). For example, in an experiment using a radial arm maze, a change in the

geometry of the room dropped the performance of control males and females who had been treated with estradiol benzoate. In contrast, the geometry change did not affect the performance of control females or males who had been neonatally castrated (Williams, Barnett, & Meck, 1990). Thus, findings of dominance of geometric information may depend on the sex of the animals. If this is correct, note that there is no easy way for the modularity position to explain how participant sex would affect reliance on geometric information.

2. However, there are a few things to note about Wall et al.'s study. First, accuracy with the feature panel in the first step of learning in the square was not impressively high. The rats were only 67% accurate. Thus, when they were transferred to the rectangular arena, additional learning was likely to be ongoing and could have included the geometric information. Unfortunately, the study is lacking a geometry-only control group. It would be helpful to compare the learning curve when geometry is presented on its own to one group of rats to the learning rate of geometry in rats that had previously learned that the black feature panel predicted the food location.
3. A reviewer pointed out that the small-large dot comparison may create an illusion of depth. It may appear to participants that the square is really a rectangle, and that perceived geometry that could be used for reorientation. If there is an illusion of size, it is particularly unlikely because of the small size of the search space. Illusions based on depth cues are particularly weak in small spaces. Additionally, as multiple trials are administered with the children moving through the space, they would have an opportunity to interact with the space and identify the enclosure as a true square (S. F. Lourenco, personal communication, June 29, 2009).

Acknowledgments

Preparation of this paper was supported by NSF BSC 0414302 and SBE 0541957. An earlier version of the paper was presented in a symposium at the Psychonomic Society in November 2007. Thanks to Vladimir Sloutsky for organizing the symposium and also assembling papers for a special issue, to the reviewers for their probing comments, and to the personnel and parents of the Temple Infant Lab for participation in experiments.

References

- Acredolo, L. P. (1978). Development of spatial orientation in infancy. *Developmental Psychology, 14*, 224–234.
- Acredolo, L. P., & Evans, D. (1980). Developmental change in the effects of landmarks on infant spatial behavior. *Developmental Psychology, 16*, 312–318.
- Barrett, H. C., & Kurzban, R. (2006). Modularity in cognition: Framing the debate. *Psychological Review, 113*, 628–647.
- Batty, E. R., Bloomfield, L. L., Spetch, M. L., & Sturdy, C. B. (2009). Comparing black-capped (*Poecile atricapillus*) and mountain chickadees (*Poecile gambeli*): Use of geometric and featural information in a spatial orientation task. *Animal Cognition, 12*, 633–641.

- Begley, S. (2009). Why do we rape, kill, and sleep around? *Newsweek*. Available at: <http://www.newsweek.com/id/202789>. Accessed June 26, 2009.
- Benhamou, S., & Poucet, P. (1998). Landmark use by navigating rats (*Rattus norvegicus*): Contrasting geometric and featural information. *Journal of Comparative Psychology*, *112*, 317–322.
- Biegler, R., & Morris, R. G. M. (1999). Blocking in the spatial domain with arrays of discrete landmarks. *Journal of Experimental Psychology: Animal Behavior Processes*, *25*, 334–351.
- Brooks, D. (2009). Human nature today. *New York Times*. Available at: <http://www.nytimes.com/2009/06/26/opinion/26brooks.html>. Accessed June 26, 2009.
- Brown, A. A., Spetch, M. L., & Hurd, P. L. (2007). Growing in circles: Rearing environment alters spatial navigation in fish. *Psychological Science*, *18*, 569–573.
- Bullens, J., Nardini, M., Doeller, C. F., Braddick, O., Postma, A., & Burgess, N. (2009). The role of landmarks and boundaries in the development of spatial memory. *Developmental Science*, doi: 10.1111/j.1467-7687.2009.00870.x.
- Carruthers, P. (2006). *The architecture of the mind: Massive modularity and the flexibility of thought*. New York: Clarendon Press/Oxford University Press.
- Cheng, K. (1986). A purely geometric module in the rats spatial representation. *Cognition*, *23*, 149–178.
- Cheng, K. (2008). Wither geometry? Troubles of the geometric module. *Trends in Cognitive Sciences*, *12*, 355–361.
- Cheng, K., & Gallistel, C. R. (2005). Shape parameters explain data from spatial transformations: Comment on Peace et al. (2004) and Tommasi & Polli (2004). *Journal of Experimental Psychology: Animal Behavioral Processes*, *31*, 254–259.
- Cheng, K., & Newcombe, N. S. (2005). Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychonomic Bulletin & Review*, *12*, 1–23.
- Cheng, K., Shettleworth, S. J., Huttenlocher, J., & Rieser, J. J. (2007). Bayesian integration of spatial information. *Psychological Bulletin*, *133*, 625–637.
- Cheung, A., Sturzl, W., Zeil, J., & Cheng, K. (2008). The information content of panoramic image II: View based navigation in nonrectangular experimental arenas. *Journal of Experimental Psychology: Animal Behavioral Processes*, *34*, 15–30.
- Chiandetti, C., Regolin, L., Sovrano, V. A., & Vallortigara, G. (2007). Spatial reorientation: The effects of space size on the encoding of landmark and geometry information. *Animal Cognition*, *10*, 159–168.
- Chiandetti, C., & Vallortigara, G. (2008). An innate geometric module? Effects of experience with angular geometric cues on spatial reorientation based on the shape of the environment. *Animal Cognition*, *11*, 139–146.
- Cosmides, L., & Tooby, J. (1992). Cognitive adaptations for social exchange. In J. H. Barkow, L. Cosmides, & J. Tooby (Eds.), *The adapted mind* (pp. 163–228). New York: Oxford University Press.
- Cressant, A., Muller, R. U., & Poucet, B. (1997). Failure of centrally placed objects to control the firing fields of hippocampal place cell. *Journal of Neuroscience*, *17*, 2531–2542.
- Dawson, M. R. W., Kelly, D. M., Spetch, M. L., & Dupuis, B. (2008). Learning about environmental geometry: A flaw in Miller and Shettleworth's (2007) operant model. *Journal of Experimental Psychology: Animal Behavioral Processes*, *34*, 415–418.
- Dessalegn, B., & Landau, B. (2008). More than meets the eye: The role of language in binding visual properties. *Psychological Science*, *19*, 189–195.
- Diez-Chamizo, V., Sterio, D., & Mackintosh, N. J. (1985). Blocking and overshadowing between intramaze and extramaze cues: A test of the independence of locale and guidance learning. *Quarterly Journal of Experimental Psychology*, *37B*, 235–253.
- Doeller, C. F., & Burgess, N. (2008). Distinct error-correcting and incidental learning of location relative to landmarks and boundaries. *Proceedings of the National Academy of Sciences*, *105*, 5909–5914.
- Doeller, C. F., King, J. A., & Burgess, N. (2008). Parallel striatal and hippocampal systems for landmarks and boundaries in spatial memory. *Proceedings of the National Academy of Sciences*, *105*, 5915–5920.

- Elman, J., Bates, E., Johnson, M., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: MIT Press.
- Fodor, J. A. (1983). *The modularity of mind*. Cambridge, MA: MIT Press.
- Fodor, J. A. (2000). Replies to critics. *Mind & Language*, 15, 350–374.
- Foster, T., Castro, C., & McNaughton, B. (1989). Spatial selectivity of rat hippocampal neurons: Dependence on preparedness for movement. *Science*, 244, 1580–1582.
- Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: MIT Press.
- Gouteux, S., Thinus-Blanc, C., & Vauclair, J. (2001). Rhesus monkeys use geometric and nongeometric information during a reorientation task. *Experimental Psychology General*, 130, 505–519.
- Graham, M., Good, M. A., McGregor, A., & Pearce, J. M. (2006). Spatial learning based on the shape of the environment is influenced by properties of the objects forming the shape. *Journal of Experimental Psychology: Animal Behavioral Processes*, 32, 44–59.
- Gray, E. R., Bloomfield, L. L., Ferrey, A., Spetch, M. L., & Sturdy, C. B. (2005). Spatial encoding in mountain chickadees: Features overshadow geometry. *Biology Letters*, 1, 314–317.
- Hamilton, D. A., & Sutherland, R. J. (1999). Blocking in human place learning: Evidence from virtual navigation. *Psychobiology*, 27, 453–461.
- Hardt, O., Hupbach, A., & Nadel, L. (2009). Factors moderating blocking in human place learning: The role of task instructions. *Learning & Behavior*, 37, 42–59.
- Hermer, L., & Spelke, E. (1994). A geometric process for spatial representation in young children. *Nature*, 370, 57–59.
- Hermer, L., & Spelke, E. (1996). Modularity and development: The case of spatial reorientation. *Cognition*, 61, 195–232.
- Hermer-Vazquez, L., Moffet, A., & Munkholm, P. (2001). Language, space, and the development of cognitive flexibility in humans: The case of two spatial memory tasks. *Cognition*, 79, 263–299.
- Hermer-Vazquez, L., Spelke, E., & Katsnelson, A. (1999). Sources of flexibility in human cognition: Dual task studies of space and language. *Cognitive Psychology*, 39, 3–36.
- Horne, M. R., & Pearce, J. M. (2009). A landmark blocks searching for a hidden platform in an environment with a distinctive shape after extended pretraining. *Learning & Behavior*, 37, 167–178.
- Hull, C. L. (1943). *Principles of behavior. An introduction to behavior theory*. New York: Appleton-Century.
- Hupbach, A., Hardt, O., Nadel, L., & Bohbot, V. D. (2007). Spatial reorientation: Effects of verbal and spatial shadowing. *Spatial Cognition and Computation*, 7, 213–226.
- Hupbach, A., & Nadel, L. (2005). Reorientation in a rhombic environment: No evidence for an encapsulated geometric module. *Cognitive Development*, 20, 279–302.
- Huttenlocher, J., & Lourenco, S. F. (2007). Coding location in enclosed spaces: Is geometry the principle? *Developmental Science*, 10, 741–746.
- Huttenlocher, J., & Vasilyeva, M. (2003). How toddlers represent enclosed spaces. *Cognitive Science*, 27, 749–766.
- Jonasson, Z. (2005). Meta-analysis of sex differences in rodent models of learning and memory: A review of behavioral and biological data. *Neuroscience and Biobehavioral Reviews*, 28, 811–825.
- Karmiloff-Smith, A. (1992). *Beyond modularity: A developmental perspective on cognitive science*. Cambridge, MA: MIT Press.
- Kelly, D. M., Spetch, M. L., & Heth, C. D. (1998). Pigeons' (*Columba livia*) encoding of geometric and featural properties of a spatial environment. *Journal of Comparative Psychology*, 112, 259–269.
- Kinzler, K. D., & Spelke, E. S. (2007). Core systems in human cognition. *Progress in Brain Research*, 164, 257–264.
- Kjelstrup, K. B., Solstad, T., Brun, V. H., Hafting, T., Leutgeb, S., Witter, M. P., Moser, E. I., Moser, M. B. (2008). Finite scale of spatial representation in the hippocampus. *Science*, 321, 140–143.
- Landau, B., & Lakusta, L. (2009). Spatial representation across species: Geometry, language, and maps. *Current Opinion in Neurobiology*, 19, 1–8.

- Learmonth, A. E., Nadel, L., & Newcombe, N. S. (2002). Children's use of landmarks: Implications for modularity theory. *Psychological Science*, *13*, 337–341.
- Learmonth, A. E., Newcombe, N. S., & Huttenlocher, J. (2001). Toddler's use of metric information and landmarks to reorient. *Journal of Experimental Child Psychology*, *80*, 225–244.
- Learmonth, A., Newcombe, N. S., Sheridan, M., & Jones, M. (2008). Why size counts: Children's spatial reorientation in large and small enclosures. *Developmental Science*, *11*, 414–426.
- Lee, S. A., Shusterman, A., & Spelke, E. S. (2006). Reorientation and landmark-guided search by young children: Evidence for two systems. *Psychological Science*, *17*, 577–582.
- Lee, S. A., & Spelke, E. S. (2008). Children's use of geometry for reorientation. *Developmental Science*, *11*, 743–749.
- Levinson, S. C. (2003). *Space in language and cognition*. Cambridge, England: Cambridge University Press.
- Lew, A. R., Foster, K. A., & Bremner, J. G. (2006). Disorientation inhibits landmark use in 12- to 18-month-old infants. *Infant Behavior & Development*, *29*, 334–341.
- Lew, A. R., Gibbons, B., Murphy, C., & Bremner, J. G. (2009). Use of geometry for spatial reorientation in children applies only to symmetric spaces. *Developmental Science*, doi: 10.1111/j.1467-7687.2009.00904.
- Lourenco, S. F., Addy, D., & Huttenlocher, J. (2009). Location representation in enclosed spaces: What types of information afford young children an advantage? *Journal of Experimental Child Psychology*, *104*, 313–325.
- Maes, J. H. R., Fontanari, L., & Regolin, L. (2009). Spatial reorientation in rats (*Rattus norvegicus*): Use of geometric and featural information as a function of arena size and feature location. *Behavioural Brain Research*, *201*, 285–291.
- McComas, J., & Dulberg, C. (1997). Children's memory for locations visited: Importance of movement and choice. *Journal of Motor Behavior*, *29*, 223–230.
- Miller, N. (2009). Modeling the effects of enclosure size on geometry learning. *Behavioural Processes*, *80*, 306–313.
- Miller, N. Y., & Shettleworth, S. J. (2008). An associative model of geometry learning: A modified choice rule. *Journal of Experimental Psychology, Animal Behavior Processes*, *34*, 419–422.
- Miller, N. Y., & Shettleworth, S. J. (2007). Learning about environmental geometry: An associative model. *Journal of Experimental Psychology, Animal Behavior Processes*, *33*, 191–212.
- Nadel, L., & Hubbach, A. (2006). Cross-species comparisons in development: The case of the spatial ‘‘module’’. In M. H. Johnson & Y. Munakata (Eds.), *Attention and performance XXI* (pp. 499–512). Oxford, England: Oxford University Press.
- Nardi, D., & Bingman, V. P. (2009). Pigeon (*Columba livia*) encoding of a goal location: The relative importance of shape geometry and slope information. *Journal of Comparative Cognition*, *123*, 204–216.
- Nardini, M., Atkinson, J., & Burgess, N. (2008). Children reorient using the left/right sense of coloured landmarks at 18–24 months. *Cognition*, *106*, 519–527.
- Nardini, M., Thomas, R. L., Knowland, V. C. P., Braddick, O. J., & Atkinson, J. (2009). A viewpoint-independent process for spatial reorientation. *Cognition*, *112*, 241–248.
- Newcombe, N. S. (2005). Language as destiny? Or not—Essay review of space in language and cognition: Explorations in cognitive diversity by Stephen C. Levinson. *Human Development*, *48*, 309–314.
- Newcombe, N. S., & Huttenlocher, J. (2006). Development of spatial cognition. In W. Damon & R. Lerner (Series Eds.) and D. Kuhn & R. Siegler (Vol. Eds.), *Handbook of child psychology: Vol. 2. Cognition, perception and language*, 6th ed. (pp. 734–776). Hoboken, NJ: John Wiley & Sons.
- Newcombe, N. S., & Ratliff, K. R. (2007). Explaining the development of spatial reorientation: Modularity-plus-language versus the emergence of adaptive combination. In J. Plumer & J. Spencer (Eds.), *The emerging spatial mind* (pp. 53–76). New York: Oxford University Press.
- Newcombe, N. S., Ratliff, K. R., Shallcross, W. L., & Twyman, A. (2009). Young children really can reorient using features: Further evidence against a modular view of spatial processing. *Developmental Science*, *5*, 1–8.
- Pearce, J. M., Graham, M., Good, M. A., Jones, P. M., & McGregor, A. (2004). Transfer of spatial behavior between different environments: Implications for theories of spatial learning and for the role of the hippocampus in spatial learning. *Journal of Experimental Psychology: Animal Behavior Processes*, *30*, 135–147.

- Pearce, J. M., Graham, M., Good, M. A., Jones, P. M., & McGregor, A. (2006). Potentiation, overshadowing, and blocking of spatial learning based on the shape of the environment. *Journal of Experimental Psychology: Animal Behavior Processes*, 32, 201–214.
- Presson, C. C., & Montello, D. R. (1988). Points of reference in spatial cognition: Stalking the elusive landmark. *British Journal of Developmental Psychology*, 6, 378–381.
- Ratliff, K. R., & Newcombe, N. S. (2008a). Is language necessary for human spatial reorientation? Reconsidering evidence from dual task paradigms. *Cognitive Psychology*, 56, 142–163.
- Ratliff, K. R., & Newcombe, N. S. (2008b). Reorienting when cues conflict: Evidence for an adaptive combination view. *Psychological Science*, 19, 1301–1307.
- Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: Variations in the effectiveness of reinforcement and nonreinforcement. In A. G. Black & W. F. Prokasy (Eds.), *Classical conditioning II: Current research and theory* (pp. 64–99). New York: Appleton-Century-Crofts.
- Roberts, A. D. L., & Pearce, J. M. (1999). Blocking in the Morris swimming pool. *Journal of Experimental Psychology—Animal Behavior Processes*, 25, 225–235.
- Rodrigo, T., Chamizo, V. D., McLaren, I. P. L., & Mackintosh, N. J. (1997). Blocking in the spatial domain. *Journal of Experimental Psychology—Animal Behavior Processes*, 23, 110–118.
- Sheynikhovich, D., Chavarriga, R., Strösslin, T., Arleo, A., & Gerstner, W. (2009). Is there a geometric module for spatial orientation? Insights from a rodent navigation model. *Psychological Review*, 116, 540–566.
- Shusterman, A., & Spelke, E. S. (2005). Language and the development of spatial reasoning. In P. Carruthers, S. Laurene, & S. Stich (Eds.), *The innate mind: Structure and contents* (pp. 89–106). New York: Oxford University Press.
- Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. New York: Oxford University Press.
- Smith, A. D., Gilchrist, I. D., Cater, K., Ikram, N., Nott, K., & Hood, B. M. (2008). Reorientation in the real world: The development of landmark use and integration in a natural environment. *Cognition*, 107, 1102–1111.
- Solstad, T., Boccaro, C. N., Kropff, E., Moser, M., & Moser, E. I. (2008). Representation of geometric borders in the entorhinal cortex. *Science*, 322, 1865–1868.
- Sovrano, V. A., Bisazza, A., & Vallortigara, G. (2007). How fish do geometry in large and in small spaces. *Animal Cognition*, 10, 47–54.
- Sovrano, V. A., & Vallortigara, G. (2006). Dissecting the geometric module: A sense-linkage for metric and landmark information in animals' spatial reorientation. *Psychological Science*, 17, 616–621.
- Spelke, E. S. (2008). The theory of “core knowledge.” *Annee Psychologique*, 108, 721–756.
- Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental Science*, 10, 89–96.
- Spetch, M. L. (1995). Overshadowing in landmark learning—touch-screen studies with pigeons and humans. *Journal of Experimental Psychology—Animal Behavior Processes*, 21, 166–181.
- Sturzl, W., Cheung, A., Cheng, K., & Zeil, J. (2008). The information content of panoramic images I: The rotational error and the similarity of view in rectangular experimental arenas. *Journal of Experimental Psychology: Animal Behavioral Processes*, 34, 1–14.
- Taube, J. S. (1998). Head direction cells and the neurophysiological basis for a sense of direction. *Progress in Neurobiology*, 55, 225–256.
- Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, 55, 189–208.
- Twyman, A., Friedman, A., & Spetch, M. L. (2007). Penetrating the geometric module: Catalyzing children's use of landmarks. *Developmental Psychology*, 43, 1523–1530.
- Twyman, A., Newcombe, N. S., & Gould, T. J. (2009). Tale of two cities: Rearing environment influences spatial reorientation. In S. E. MacDonald (Chair), *Foraging and the evolution of cognition*. Symposium conducted at the meeting of the APA convention, Toronto, Canada.
- Twyman, A., Newcombe, N. S., & Gould, T. J. (2009). Of mice (*Mus musculus*) and toddlers (*Homo sapiens*): Evidence against modularity in spatial reorientation. *Journal of Comparative Psychology*, 123, 342–345.
- Vallortigara, G., Sovrano, V. A., & Chiandetti, C. (2009). Doing Socrates experiment right: Controlled rearing studies of geometrical knowledge in animals. *Current Opinion in Neurobiology*, 19, 20–26.

- Vallortigara, G., Zanforlin, M., & Pasti, G. (1990). Geometric modules in animals' spatial representations: A test with chicks (*Gallus gallus domesticus*). *Journal of Comparative Psychology*, *104*, 248–254.
- Vlasak, V. A. (2006). The relative importance of global and local landmarks in navigation by Columbian ground squirrels (*Spermophilus columbianus*). *Journal of Comparative Psychology*, *120*, 131–138.
- Wall, P. L., Botly, L. C. P., Black, C. K., & Shettleworth, S. J. (2004). The geometric module in the rat: Independence of shape and feature learning in a food finding task. *Learning & Behavior*, *32*, 289–298.
- Williams, C. L., Barnett, A. M., & Meck, W. H. (1990). Organizational effects of early gonadal secretions on sexual-differentiation in spatial memory. *Behavioral Neuroscience*, *104*, 84–97.
- Woodruff-Pak, D., Papka, M., & Ivry, R. (1996). Cerebellar involvement in eyeblink classical conditioning in humans. *Neuropsychology*, *10*, 443–458.
- Wystrach, A., & Beugnon, G. (2009). Ants learn geometry and features. *Current Biology*, *19*, 61–66.