

Explaining the Development of Spatial Reorientation:
Modularity-Plus-Language Versus the Emergence of Adaptive Combination

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All mobile organisms occasionally face the important adaptive problem of determining where they are when they have been disoriented by rapid movement (e.g., tumbling down a hill) or passive movement without visual landmarks (e.g., as occurs when people travel by subway). It has recently been proposed that a wide array of non-human animal species, as well as human children, solve this problem using a geometric module that only accepts information about the shape of enclosing spaces (Cheng, 1986; Gallistel, 1990; Hermer & Spelke, 1994, 1996; see Cheng & Newcombe, 2005 for an overview). In a modular view, various sources of spatial information are processed independently in separable cognitive processing units (e.g., Wang & Spelke, 2002). Starting at 6 years of age in humans, however, investigators have argued that productive control of spatial language, specifically the terms “right” and “left”, allows the operation of this geometric module to be supplemented by the use of featural information, such as the color of surfaces in the environment (e.g., Hermer-Vazquez, Moffett, & Munkholm, 2001; Hermer-Vazquez, Spelke & Katsnelson, 1999).

Modularity is typically associated with nativist views (although this relation is by no means forced by logic; Fodor, 2001). However, there is a problem for innatist modularity claims: how to explain developmental change. In the case of the geometric module, Spelke and her associates have solved the problem of why features as well as geometry start to be used to reorient by postulating what is essentially a grafting process. In such a process, use of features as well as geometry occurs when the language faculty (which itself can be argued to be a largely innate module) matures sufficiently to supplement the output of its sister module. In this formulation, Vygotsky supplements Chomsky and Fodor to explain

development.¹ This “modularity-plus-language” view has only two explanatory mechanisms: innate endowment and linguistic mediation.

There are alternatives, however, to the modularity-plus-language position and its simple explanation of developmental change. There is a good deal of evidence, in a variety of domains, that information sources are frequently combined to determine judgments and behavior, using weighting mechanisms. For example, judgments of an object’s size can be based on information from either vision or touch; when both kinds of information are available, people combine the two sources in a fashion weighted by the variance associated with each source (Banks, 2005; Ernst & Banks, 2002). This integration rule is an application of Bayes’ rule, and leads to judgments that approach statistical optimality. In the spatial domain, Huttenlocher, Hedges and Duncan (1991; see also Huttenlocher and Lourenco, this volume) have proposed a hierarchical combination model, in which estimates of an object’s location are based on a combination of fine-grained and categorical information. These sources of information are combined according to Bayesian rules in a fashion that depends on the certainty with which each kind of information has been coded (with greater uncertainty associated with greater variance). Also in the spatial domain, Hartley, Trinkler and Burgess (2004) have developed a *boundary proximity model* of human memory for location within enclosed spaces that uses a mixture of absolute and relative distance information. Encoding of absolute distance from a wall is more accurate and less variable when the distance is short, while encoding of relative distances (ratios of distances from various walls) is less dependent on how close a location is to a wall. Hence, absolute information is weighted more heavily when encoding locations close to walls while relative information is weighted more heavily when walls are distant (i.e., when a location is in the middle of the enclosure).

The overall family of such approaches to understanding estimation and judgment tasks can be called the adaptive combination view (Newcombe & Huttenlocher, 2006). The three specific models we have mentioned so far concentrate on uncertainty and variability in encoding of various kinds of information, all of which are clearly relevant to the task at hand. However, there may be additional influences on weighting. Notably, the salience of various kinds of information would clearly be expected

to affect probability of use. Even more important for development, an organism's history of using particular kinds of information (i.e., learning) would naturally affect the weighting placed on that information source (as is envisioned in connectionist models of development). In terms of the task of re-establishing spatial orientation, an adaptive combination view suggests the possibility that geometric and featural information are utilized in varying degrees at varying points in development, in a fashion that reflects the certainty and variance with which the two kinds of information are encoded, along with their salience and perceived usefulness.

The adaptive combination viewpoint is a general one, which could potentially be applied to many lines of cognitive development, not just the spatial domain. It is also a view point that has elements in common with several current approaches to cognitive development, including connectionism, dynamic systems, and Siegler's overlapping waves theory (see discussion in Newcombe & Huttenlocher, 2006). It has an empiricist flavor, because it seems natural to suppose that the weightings in an integrative process are affected by experience. However, there are potentially nativist elements as well. Initial weightings might be, at least in part, innately specified, and what kinds of information are treated as relevant to what kinds of actions may well need to be set at an appropriate starting point. It is also possible that a Bayesian learning process is itself a basic attribute of the organism rather than acquired (cf. Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996).

The purpose of this chapter is to discuss these two views—modularity-plus-language and adaptive combination—concentrating particularly on the issue that most clearly demarcates them, namely modularity. The plan of this chapter is as follows. First, we discuss what is meant by the term “module”. It is a term in very widespread use, but different people mean quite different things by it. Second, we describe in greater detail the evidence favoring the geometric module hypothesis and the further hypothesis that it can be augmented by spatial language (for a more extended review, see Cheng & Newcombe, 2005). Third, we present reasons to doubt the modularity-plus-language view. Fourth, we consider how an adaptive combination approach would describe the known phenomena, what predictions it would make, and how it would address potential criticisms.

What Do We Mean When We Say Modularity?

Modularity has been an extremely attractive concept in cognitive science recently, and has even received wide attention in the popular scientific press. For example, one science journalist has written with authority that “your brain is not a general-purpose computer with one unified central processor. It is an assemblage of competing subsystems—sometimes called “modules”—specialized for particular tasks” (S. Johnson, 2004, p. 26). In fact, it has become increasingly common to hear the claim that the mind/brain is *massively* modular, that is, that it consists of an assemblage of modules (e.g., Pinker, 1997, Sperber, 1994; but see Fodor, 2001, and Buller, 2005, for doubts). This trend is correlated with several other trends in cognitive and developmental science: interest in the evolutionary bases of cognition; a frequent focus on separate cognitive domains, such as spatial competence, as well as (or sometimes to the exclusion of) domain-general faculties, such as attention; neuroscience findings concerning the specific cortical areas that support cognitive functions; and, widespread acceptance of the idea that many cognitive capabilities have strong innate bases. Painting with a broad brush, many investigators have embraced the view that evolution has selected for particular cognitive skills that are present at least in skeletal form at birth and that are supported by discrete areas of the brain. However, these various lines of thought are not as tightly and inevitably woven together as appears at first, and the term “modularity” means different things to different people. In this section, we analyze how best to use the term with precision.

A useful place to begin is with Fodor’s (1983) *The Modularity of Mind*. This book is, arguably, the historical starting point for discussion of modularity in cognitive science. There are three interesting aspects of Fodor’s (1983) treatment of the term modularity. First, he strongly emphasized the functional isolation of cognitive modules, an element of modularity that has often been ignored in subsequent research. For instance, he wrote that, “What I take to be perhaps the most important aspect of modularity [is] something that I shall call ‘informational encapsulation’ ”. (p. 37). Encapsulation is illustrated by the example of the Muller Lyer illusion (see Figure 1). No matter how certain a person is that the horizontal lines in such a figure are in fact equal in length, it is not possible to see them as equal. The line with the

outward facing arrows always looks longer. Thus, the visual system is encapsulated (or, to use a synonym, impenetrable) with respect to conscious knowledge.

A second interesting aspect of Fodor's (1983) book is that he argued that only input systems are likely to be modular: "[c]entral systems are, in important respects, *unencapsulated*, and .. it is primarily for this reason that they are not plausibly viewed as modular." (p. 103). This position differs markedly from subsequent usage by many cognitive scientists, who have freely postulated such central modules as a theory of mind module or a cheater detection module (e.g., Scholl & Leslie, 1999; Cosmides & Tooby, 1992; but see also Buller, 2005). Fodor argued that central systems such as thinking, reasoning and decision-making, could not be modular because "the representations that input systems deliver have to interface somewhere" (pp. 101-2).

A third important aspect of Fodor's (1983) treatment of modularity is that he emphasized the linkage between modularity and the concepts that are now virtually synonymous with it in the minds of many cognitive scientists: domain specificity, nativism, and neural specialization. He wrote quite specifically that "modular cognitive systems are domain specific, innately specified, hard wired, autonomous, and not assembled." (p. 37). While he did not explicitly mention adaptive value and natural selection (and, in his 2001 book, doubted the extent of the connection between modularity and these concepts), the idea that modular cognitive systems are created by evolutionary forces seems very attractive to many other theorists (e.g., Pinker, 1997). Today, these various terms are often used virtually interchangeably. For example, in a recent article on working memory, domain specificity and modularity were regarded as equivalent: "One model, developed by Goldman-Rakic and colleagues, postulates a modular organization of working memory based on the type of information processing (the domain specificity hypothesis)," (Romanski, 2004, p. 421). Similarly, again choosing a convenient recent example, Akhtar (2004, p. 459) equates nativism and modularity in writing that "The main goal of nativists ... is to verify a specific theory of linguistic competence that suggests that linguistic knowledge is innate and modular".

Modularity should not, however, be casually regarded as synonymous with nativism, domain specificity, neural specialization, or abilities shaped by evolution. Each of these concepts is historically correlated with modularity, but each of them could be true without modularity being true, and their validity needs to be considered independently. Let us begin with the relation of modularity and nativism, for which reflection reveals that neither concept strictly entails the other. On the one hand, modularity could be emergent and hence *not* nativist (e.g., Karmiloff-Smith, 1992). On the other hand, there could conceivably be strong innate determination of cognitive capacities and representations without a modular organization of mind. Indeed, revising his 1983 views, Fodor (2001, pp. 57-58) now says that “the argument between nativists and empiricists that Chomsky revived is orthogonal to the argument over whether, and to what extent, mental processes are encapsulated.” Nevertheless, the relation between modularity and nativism is a tricky one, both because the two ideas are strongly correlated in the minds of many cognitive developmentalists, and also because the question of what evidence counts for and against a nativist position is actually fairly unclear (Newcombe, 2002).

Modularity and nativism are independent but the case is different for the other three concepts correlated with modularity (i.e., domain specificity, neural specialization, and abilities shaped by evolution). For these concepts, there are entailments, but the entailments are asymmetric, at least as long as modularity is taken to include encapsulation. That is, modularity implies the other concepts, but the other concepts do not imply modularity. Although it is hard to imagine how an encapsulated module could be domain-general, domain specificity does not require encapsulation. That is, domain-specific aspects of the cognitive system, such as spatial working memory, need not be isolated from other cognitive functions.² In fact, for most specialized systems like this, isolation might destroy their usefulness. Similarly, while any encapsulated module would seem to require support from a specialized neural area³, neural specialization does not entail modularity. If specialized brain areas ‘talk to’ one another to support a function, as they almost always do, there is no encapsulation.

Finally, while modularity would not be likely to exist without evolutionary pressure, adaptive problems can be solved without modularity. Evolutionary psychology has been strongly identified with

the Swiss army knife metaphor of mental life, in which the mind/brain is analogically mapped to a bundle of tools, each well-designed for solving a different problem – scissors for cutting paper in the case of the Swiss army knife, foraging for food, avoiding predators, and navigating a landscape in the case of the mind/brain. However, even if one accepts this analogy, encapsulated modules are not necessarily implied. One of the originators of evolutionary cognitive psychology, Leda Cosmides, has in fact said in an on-line interview that, “I have discovered that some people misunderstand the Swiss Army knife metaphor – they think the claim is that these programs do not share information or work together. All these functionally specialized, domain-specific programs are designed to work together to produce behavior. They share information, pass it back and forth, and so on.”

Where does this leave the matter of what we should mean when we say “modularity”?

Investigators clearly have many correlated attributes in mind when they use the term, yet these vary across theorists and not all of the attributes are necessary and sufficient parts of a rigorous definition of the term. In fact, if the encapsulation criterion is not met, it is not clear that the term “module” is helpful at all (see Fodor, 2001; Seok, 2006). It would likely be better to be specific, to say “domain specificity” if that is what is meant, or “dependent on a specific cortical area” if that is what is meant, and so on. Investigators are, of course, free to use a term like modularity without requiring encapsulation if they like, but little is gained and much may be lost by doing so, because readers are left with a false sense of functional separation where there may be none intended. As Lewis Carroll wrote in a different context: “The question is,” said Alice, “whether you can make words mean so many different things.

Given this background, we can now turn back to the tale of the geometric module itself. The geometric module is an interesting test case for the utility of the modularity concept, precisely because bold claims have been made for its encapsulation. Other “modules” may simply be cases of developmentally-emergent functions with domain-specific properties supported by specialized brain areas that have adaptive functions. An important reason to be interested in the geometric module is that it is one of the few modules of the many that have been proposed that seems to meet Fodor’s encapsulation criterion. When investigators discuss other hypothesized modules, such as a theory of mind module or a

cheater detection module, they rarely make such bold claims about encapsulation. Thus, the existence or non-existence of an encapsulated geometric module is a matter of considerable interest, because demonstrating the phenomenon securely would show that there could be a cognitively-interesting module that corresponds to Fodor's (1983) conceptualization. In fact, a modular spatial reorientation system might be an example of what Fodor thought unlikely, namely, a modular central system.

Evidence Favoring the Modularity-Plus-Language View

When we emerge from a subway station, we look around for clues as to which way we are facing, and how to relate what we see to our knowledge of the spatial relations in the current environment. Similarly, animals that have just been engaged in rough-and-tumble play with other animals might, once the engagement is complete, search for information about how they are now placed in the environment. Cheng (1986) made the fascinating discovery that, following disorientation of this kind, animals reorient using the metric information given by the lengths and angles that form the shape of the surrounding environment. Specifically, he trained rats to find food hidden in one corner of a rectangular cage with unmarked walls, for example, in one of the two corners where a long wall is to the left of a short wall. As long as the rats remained oriented, they could distinguish between the two corners having the same geometric characteristics. However, once they were disoriented, the rats searched for the reward equally often at the geometrically identical corners.

A further aspect of Cheng's experiments showed that the animals did not simply use geometric information—they also relied on it to the exclusion of nongeometric information that would augment it and make it possible to search correctly. When the rectangular cage had additional landmarks, such as wall markings or smells, that remove the ambiguity between the congruent corners, the rats did not use the landmark information. Rather, they continued to divide search evenly between the correct and reverse corners. Thus, Cheng showed that the rats encoded the geometric properties of the space (i.e., the length of the walls and their relation at the corners), but did not incorporate the nongeometric features in their representation of the room to guide their reorientation. Gallistel (1990) cited these data prominently in his extended arguments for the existence of a geometric module.

Human children, 18 to 24 months, have shown similar search patterns for a hidden toy within a symmetric rectangular environment (Hermer & Spelke, 1994; 1996). In a rectangular room with all white walls, young children used geometric information to reorient within the room, dividing their searches for the hidden toy evenly between the correct and reverse corners. When a colored wall was added, although children should have enough information to distinguish the correct corner and to successfully complete the task, children's search rates remained identical to those in the all white room. Hermer and Spelke proposed that children's failure to conjoin the geometric and nongeometric information was based on their use of an encapsulated and task-specific mechanism: the geometric module.

Although rats and children both show evidence of a dominant geometric representation that guides reorientation to the neglect of nongeometric information, human adults easily combine geometric and nongeometric spatial information to reorient in a symmetric environment. Hermer-Vazquez et al. (1999) found that, following disorientation in a rectangular room with all white walls and one blue wall, human adults showed no encapsulation, successfully reorienting to find the correct corner of the room as expected. However, when adults were simultaneously engaged in a verbal interference task, they were no longer able to flexibly combine the two kinds of information and were limited to using only the geometric information to reorient. Adults who performed a nonverbal control task were easily able to combine geometric and nongeometric information to reorient. These data suggest that the joint use of featural and geometric information requires linguistic support. Hermer-Vazquez et al. (1999) concluded that adults are able to overcome the encapsulation found among young children by acquiring spatial language and engaging linguistic processing to utilize nongeometric features in conjunction with geometric information. Specifically, Hermer-Vazquez et al. (1999) claimed that the language faculty serves as a system of representation which connects to other systems of representation, allowing the arbitrary combination of information from distinct sources.

Children develop the ability to appropriately use the spatial terms "left" and "right" around the age of six years. This age is also the one at which they successfully complete the reorientation task using features. Hermer-Vazquez et al. (2001) investigated this coincidence of ages further. They gave a variety

of cognitive tests, including nonverbal intelligence, digit span, visuospatial span, production of spatial terms (above-below, in front-behind, left-right), and comprehension of these same spatial terms to a group of children around this age, as well as testing them in the reorientation task. They reported that the only variable that predicted children's ability to reorient using features as well as geometry was their production of the terms "left" and "right". Based on these data, they argued that control of such linguistic terms was essential in allowing for rapid and flexible use of features in reorientation.

Evidence Against the Modularity-Plus-Language View

Taken together, the data from rats, human children and human adults seem to make a powerful and elegant case for an encapsulated geometric module that is present in early development and perhaps innate, but that is eventually supplemented (one might even say "breached" or "pierced") by the use of language. However, there is also contradictory evidence. The data that cast doubt on the notion of an encapsulated geometric module come first from non-human animals. In the absence of language, it would seem unlikely that they would ever use features to reorient, yet many studies have shown that they do. We review some illustrative work here (see Cheng & Newcombe, 2005 for a more complete discussion). Although the work with non-human animals might seem decisive, the data from humans used to support the modularity-plus-language view uses a different paradigm that involves much less training, and thus the story of human development requires separate consideration. We review evidence that very young children do sometimes use features as well as geometry to reorient. We also examine further the claim that human adults can only use features as well as geometry to reorient when their linguistic capacity is not otherwise engaged through verbal shadowing.

No Encapsulation in Non-Human Animals

In experiments using chickens, Vallortigara, Zanforlin, and Pasti (1990) found that the birds utilized direct features in their reorientation within a rectangular enclosure. As seen previously with rats, when no distinguishing features were present in the space, the chickens relied on geometric encoding to guide their searches for food at the geometrically identical corners (correct and opposite). Unlike rats,

however, once four distinctive panels were placed on each corner, the chickens were able to use the direct featural information to disambiguate the space and search the correct corner.

Kelly, Spetch and Heth (1998) found similar results using pigeons, in that the birds used both direct and indirect nongeometric information in conjunction with the geometry of the room shape to guide their search for food following disorientation in a rectangular enclosure. Some pigeons were trained with featural information available in the corners throughout the entirety of the experiments whereas other pigeons initially only had an ambiguous symmetric enclosure. All pigeons used the room shape to guide their reorientation, and once features were added for all environments, the pigeons successfully used both geometric and nongeometric information. When the nongeometric features were in conflict with the geometry of the room (achieved through rotating the feature panels), the history of the pigeon's exposure to the featural cues affected their reliance on them. The pigeons trained with featural information available from the first trial showed a reliance on nongeometric information, whereas the pigeons trained initially only with geometry showed a mixture of using features and geometry.

Monkeys also show no encapsulation, using both geometric and nongeometric knowledge to locate a reward (Gouteux, Thinus-Blanc, & Vauclair, 2001). In a rectangular room, monkeys successfully reoriented using a colored wall to find a specific corner. Interestingly, although the monkeys used larger featural cues (i.e., a colored wall) to distinguish between the correct and incorrect corner, they did not use small featural cues. This coincides with the idea of cue validity, in that small objects are more likely to move and thus provide less stable landmarks than big objects that are more often helpful in providing a stable distal landmark.

Sovrano, Bisazza, and Vallortigara (2003) provided perhaps the most striking evidence against a geometric module with experiments using fish, specifically *xenotoca eiseni*. In a small rectangular fish tank, the fish encoded landmarks of either featured panels in each corner or a colored wall. Using the available nongeometric information in conjunction with the geometry, the fish successfully located an exit from the smaller tank to a larger, more desirable fish tank with vegetation and other fish. Interestingly, however, Sovrano et al. (2003) also found that the fish spontaneously encoded the geometric information

of the space even when the nongeometric information was all that was necessary to distinguish the correct corner, perhaps indicating the importance of relying on geometric information in addition to nongeometric information.

No Encapsulation in Very Young Children

Evidence from nonhuman animals does not support the encapsulation of a geometric module and suggests that language is *not* crucial to combining geometric and nongeometric information. Despite this strong evidence, doubts have been raised about whether animal results are sufficient to disprove the modularity-plus-language view. Hermer-Vazquez et al. (2001) argue that the nonhuman animal data are linked to extensive training, and only human adults flexibly and easily use landmarks together with geometric information in order to reorient. However, evidence against modularity has emerged with human research as well, specifically with children where minimal training has been used.

Learmonth, Newcombe, and Huttenlocher (2001) examined Hermer and Spelke's (1994, 1996) claims in experiments that differed in a few respects from the original study: (1) the room in which the experiment was conducted was four times larger than the very small room used in the original experiments (8 x 12 feet rather than 4 x 6 feet), and (2) the presence or absence of features was manipulated between groups rather than varied for a single child. Learmonth et al. confirmed the finding that disoriented children use geometric information to find a toy, indicating their ability not only to code metric extent (see also Huttenlocher, Newcombe & Sandberg, 1994) but to relate one distance to another (i.e., "the long wall to the left of the short wall"). However, when various nongeometric landmarks were added in the context of the larger room (including a colored wall in one experiment, and in other studies a door and/or a bookcase flush with the wall which could mark a toy's location either directly or indirectly), children between 17 and 24 months *did* use the nongeometric cues as well as the geometry of the space.

What accounts for this very different pattern of findings? Learmonth, Nadel and Newcombe (2002) focused on whether the size of the surrounding space was at least one of the controlling factors, and in fact confirmed that the encapsulation result appears for the small room but that nongeometric information is used in the larger room. This finding is important because it can be argued that the larger

space is a more ecologically valid setting in which to examine orientation, which after all does occur in an environment that typically extends for large distances around an active agent. That is, the Learmonth et al. studies should not be seen as a small caveat on the Hermer-Spelke result, or as simply showing that, in an easier task, geometry may not take precedence (Bertenthal, 2005). Rather, the Hermer-Spelke result should be seen as a special case that may not occur very often in nature. Data from such a situation are interesting in the same way that a visual illusion is: they may tell us something about the mind (as illusions can tell us about the visual system), but they require great care in interpretation because they do not represent a frequently-occurring pattern of functioning.

Examining the various studies of children's reorientation broken down by age groups, Cheng and Newcombe (2005) combined data across studies to create a graph of the age trends in above-chance use of geometry (i.e., choice of one of the geometrically correct corners) and use of features (i.e., choice of the unique corner identified by the feature) in the two room sizes (see Figure 2). (Values below zero are possible if participants are below chance.) At all ages studied—from toddlers to adults—participants showed above-chance use of features in the larger room. By contrast, only participants 6 years of age and older used features in the small room. Additionally, it is always more difficult to find the correct corner in the smaller room, even for the older age groups. Interestingly, although very young children do use the nongeometric information available in the large room, there is also age-related improvement in search accuracy. Specifically, using the colored wall as a landmark to distinguish between the geometrically identical corners in the large room increases both between 4 and 5 years of age and between 5 and 6 years. The idea that language is vital to use of features cannot explain the above-chance performance by toddlers in the larger room, improvement in use of features prior to acquisition of the terms left and right, or the room size effect itself.

Newcombe (2005) proposed two ways to explain the effect of room size on use of features. One possibility was that spatial orientation mechanisms may not be fully engaged in cases where it is difficult to move around in an active and exploratory way. A second explanation focused on the fact that landmarks are typically more likely to be used in spatial tasks when they are distal from, rather than close

to, an observer (see also Hupbach & Nadel, 2005; Nadel & Hupbach, in press). In a series of studies, we have explored the impact of these factors, using a paradigm in which children stay within a small centrally-located rectangular area the same size as Hermer-Spelke's room that is located within a larger rectangular room the same size as used in the Learmonth et al. experiments (Learmonth, Newcombe, Hansell & Jones, 2005). One wall of the larger room was colored. We also varied the location of the hidden toy. In our first study, it was located within the small enclosure and, thus, distant from the walls of the larger room and the feature, whereas in our second and third study it was located in a corner of the larger room adjacent to the walls. The basic results are summarized in Table 1, which also lists the Hermer-Spelke and Learmonth et al. results.

There are several interesting inferences that can be made from Table 1. First, the possibility of easy physical action seems to be important. When it is restricted, we see that success in using features to find the hidden toy occurs at a later age. Specifically, the contrast between the work of Learmonth et al. (2001, 2002) and Studies 2 and 3 is instructive. The only element of these paradigms that varies is whether or not action is restricted, and, as a function of this fact, the age at which use of features is first evident varies from 18 months when action is possible to 4 years when it is not. Second, whether the colored wall is distal or proximal also makes a difference. The age of successful use of features was 6 years in the Hermer-Spelke studies but only 4 years in Studies 2 and 3; these studies differ only in how far away the colored wall is from the child. Third, another factor that makes a difference is whether or not the target is adjacent to the space in which there is one colored wall. The age at which use of features was first observed was reduced from 6 years in Study 1, when the target was hidden in a corner of the unfeatured central enclosure, to 4 years in Studies 2 and 3, when targets were proximal to the space in which one wall was colored. In short, it turns out that both of the factors that we hypothesized might account for the room size effect have an influence, and that a third factor has been identified that has an effect as well. In addition, we note that there is nothing privileged about the 5 to 6 year transition seen in the Hermer-Spelke studies. In the bottom line of the table, we observe that there was a sudden transition to use of features that occurred between the ages of 3 and 4 years. Along similar lines, Hupbach and

Nadel (2005) found a transition at this age to use of both features and geometry in a rhombus-shaped enclosure. Such earlier transitions, before the acquisition of the terms left and right, further weakens the case for the unique importance of the acquisition of spatial language. In addition, the fact that transitions vary depending on contextual factors suggests the overall inadequacy of a modular view.

No Unique Effect of Verbal Interference in Human Adults

Given the strong evidence against a modularity-plus-language view that we have reviewed so far, why do adults *not* use nongeometric landmarks when they are engaged in a verbal interference task? We suggest that there are two possible ways to explain these results. First, in the Hermer-Vazquez et al. (1999) study, adults were simply informed prior to the disorientation procedure that, “you will see something happening that you should try to notice,” and that they would be asked about what they saw. Following these vague instructions, and with no practice trials, participants engaged in the search task with concurrent shadowing in a rectangular room with a blue wall, followed by search without shadowing in that room, and by search in an all-white room. Order was not counterbalanced. It is possible that, if given a clearer idea of the demands of the reorientation task, adult participants would search the correct corner at greater than chance levels *even while* engaged in verbal shadowing. Second, the verbal shadowing task used by Hermer-Vazquez et al. (1999) might disrupt the ability to use featural landmarks for reasons other than (or in addition to) interference with a linguistic encoding process. Another possibility is that a concurrent task reduces the ability to integrate various kinds of spatial information. Hermer-Vazquez et al. (1999) had used a nonverbal rhythm-clapping task to argue against this possibility, but this control might be inadequate because it would be expected to engage different processing mechanisms than those involved in combining types of spatial information (Newcombe, 2005).

To examine these possibilities, Ratliff and Newcombe (2005) conducted several studies using Hermer-Vazquez et al.’s (1999) dual-task paradigm, with and without modifications. With regard to the issue of understanding task demands, we found that adults who received explicit instructions as to the nature of the search task successfully integrated the nongeometric and geometric information in a rectangular white room with one blue wall, even while engaged in a verbal interference task. By contrast,

adults who received the Hermer-Vazquez et al. (1999) task exactly as they gave it found the correct corner significantly less often. The elimination of the shadowing effect with modest additional information concerning the task undermines the idea that language is absolutely necessary to the use of features to reorient.

A second issue is whether a nonverbal *spatial* interference task would impair the use of features for reorientation. Ratliff and Newcombe (2005) asked adults to perform the reorientation task while simultaneously engaging in a visual-imagery task based on a design by Brooks (1968). The spatial visualizing task significantly reduced adults' ability to use the blue wall. If language were necessary to the use of features, this task should have had no effect.

Interim Summary

Overall, these results provide substantial evidence that human and nonhuman animals use both geometric and nongeometric information to reestablish orientation to the environment. There is little evidence for an encapsulation of geometric information and perhaps even weaker evidence for the role of language in overcoming "encapsulation". Nevertheless, there are still some significant puzzles regarding the inter-relations between geometric and featural information. First, is it the case that geometric information is primary? As we have seen, features fail to be used in some situations, such as the case of young children in a very small room, but geometry seems to always be a part of the picture. Does this mean that geometric information is always more important than non-geometric information, with the latter added as a luxury or as a second step? Similarly, errors in the studies we have examined are overwhelmingly directed to the geometrically congruent corner, not to a featurally specified corner (that is, the corner made by a colored and a white wall coming together with the opposite relation of short and long from the correct corner). Why do geometric errors predominate? Does their predominance indicate the greater importance of geometric information and its possible primary nature? Second, the findings we have reviewed undermine the modularity-plus-language view, but they do not themselves directly answer the question of what framework should supplant that view or how to account for the development we see.

We turn now to an adaptive combination perspective, which we think can provide a way to think about both issues.

Adaptive Combination of Spatial Information

As described earlier, adaptive combination models suggest that the certainty and variability of the encoding of various sources of information regarding location (or anything else) determines the weight placed on the different kinds of information. Information that is less variable and more certain is more likely to be used. In addition, we noted that salience and learning history are likely also important determinants of weighting. We now turn to examining whether thinking in these terms is helpful in understanding the relatively greater reliance apparently placed on geometric than on featural information in many situations. We argue that many of the paradigms used in studies considered so far have presented geometric information that is easily encoded with great certainty and minimum variability, and that is highly salient. These situations have, in addition, often used featural information that would be expected to be encoded with more variability, or that is low in salience. Thus, we have been assessing situations in which geometric information could be expected to predominate. We go on to consider how an adaptive combination perspective helps us answer the question of mapping developmental change in spatial reorientation performance.

Why Does Geometric Information Seem to Predominate?

A fully-enclosed and regular shape can be encoded with great certainty and little if any variability. After all, the full enclosure completely and unambiguously specifies the shape, and no other shapes are possible that are consistent with the perceptually-available information. But such spaces are extremely uncommon in the natural environment. Typically, although clearly there is variation across ecologies, geometric information will occur in the form of separated aspects of the surround. For example, there might be a cliff face in the distance, a stream closer by, and a rock or a tree trunk in the immediate vicinity. Thus, a key question regarding geometric sensitivity is whether it is exhibited in cases where shape is partial and fragmentary—suggested rather than completely displayed. In this case, one may argue

that geometric information is uncertain and variable, because there is always more than one geometry that is consistent with the available evidence when there are gaps in the surrounding space.

The evidence on the use of geometric information when there is not complete enclosure suggests that geometry is less powerful in this case. For example, although Benhamou and Poucet (1998) found that rats could use the geometry of three distinct landmarks arranged in an isosceles triangle to swim to a hidden platform, rats took longer to learn in this situation than in a typical swimming pool task in which cues surrounding the pool are available (Poucet, Lenck-Santini & Save, 2003). Similarly, in studies with children where shape has been defined by objects placed at the vertices of a triangle or rectangle, it has been difficult to find evidence for early use of geometry in reorientation work (Gouteux & Spelke, 2001; but see Garrad-Cole, Lew, Bremner & Whitaker, 2001). In mapping studies, use of geometry is greatly reduced when figures are specified by dashes rather than complete lines, and even more when the figures are only indicated by their vertices (Vasilyeva, 2005). In studies where participants look at a space from the outside rather than being enclosed by it, use of geometry is also reduced (Gouteux, Vauclair & Thinus-Blanc, 2001; Hupbach & Nadel, 2005; Huttenlocher & Vasilyeva, 2003).⁴ One reason for this reduction may be that geometric information is more distinctive when viewed from inside a space, as shown in Figure 3 taken from Huttenlocher & Vasilyeva (2003).

Although we have some evidence of the effect of incomplete enclosure on use of geometry, there are additional ways in which geometry may not be as powerful as hitherto estimated. First, geometry is importantly concerned with angles as well as with length. Acquisition of the ability to use angular information to reorient only appears several years after the ability to use relative length (Hupbach & Nadel, 2005), suggesting that geometric information is not always used by very young children. Second, the salience of geometric information from relative length might be expected to vary with the ratio of long and short walls, or with the number of walls, two variables that have never been systematically manipulated.

In contrast to the use of a very strong kind of geometric information, many experiments have used features that could be predicted to be encoded variably. One of the most notable examples concerns

whether the features are distal or proximal. The location of a distal feature can be encoded with more certainty than the location of a proximal feature, because movement around a local area creates only small variations in the location of the distal feature but very large variations in the location of a local feature. We have already seen the importance of the distal versus proximal variable in the room-in-room studies, and there is further evidence of its importance from recent work with non-human animals. Fish make relatively more geometric errors when trained in a small tank and more feature errors when trained in a large tank (Sovrano, Bisazza, & Vallortigara, in press). Similarly, chicks faced with conflicting geometric and featural cues rely on geometry to reorient in a small enclosure but used features to a greater extent in a larger environment (Sovrano & Vallortigara, in press; Vallortigara, Feruglio, and Sovrano, 2005).

There are additional variables that affect the likelihood of using features. Features can be expected to be less relied on when their location is variable, and the presence of features has sometimes been varied within a single session for a single participant (e.g., Hermer & Spelke, 1996), thereby introducing a lack of certainty in encoding. In addition, experimenters have occasionally used small objects as features, which creates uncertainty because such objects frequently move with respect to target locations and hence will have a variable history of usefulness. Confirming the importance of size, Gouteux, Thinus-Blanc, & Vauclair (2001) in fact found that monkeys were more likely to use larger than smaller features to reorient. It may be argued that a colored wall, if present throughout a session, presents powerful featural information—yet consider the fact that the affordance of the wall is to prevent movement or the possibility of seeing the external world, and that the color is irrelevant to that affordance. That is, the affordance of the surface may dominate its color in encoding.

In short, research so far has mainly examined the relative use of geometry and features in situations in which geometry is instantiated in a very powerful fashion and features are less powerfully instantiated. The adaptive combination point of view would predict that reliance on geometric information will be proportionately reduced as gaps are introduced, as complexity of the shape is increased, as regularity of the shape is reduced, and as enclosure is eliminated. The adaptive combination view also

predicts that reliance on featural information will increase as features are more distal, larger, and invariantly present.

This perspective also helps to understand some otherwise puzzling results concerning overshadowing (and the lack thereof) in spatial reorientation studies. Beacons (i.e., landmarks right at the target location) typically overshadow other landmarks in spatial learning, that is, the spatial relations of the other landmarks to a target are not learned if a beacon suffices to find the target. This result has been obtained in a wide variety of species (Biegler & Morris, 1999; Diez-Chamizo, Sterio, & Mackintosh, 1985; Roberts & Pearce, 1999; Rodrigo, Chamizo, McLaren, & Mackintosh, 1997; Spetch, 1995). However, beacons do *not* seem to overshadow learning of geometry, again in a wide variety of species (Hayward, McGregor, Good, & Pearce, 2003; Kelly et al., 1998; Pearce, Ward-Robinson, Good, Fussell & Aydin, 2001; Sovrano et al., 2003; Tommasi & Vallortigara, 2000; Wall, Botly, Black, & Shettleworth, 2004). This obligatory processing of geometry has sometimes been seen as evidence for some form of modularity. However, there is another interpretation. We know that biologically salient stimuli are not subject to cue competition in some forms of learning (e.g., classical conditioning), although less salient stimuli are (Denniston, Miller, & Matute, 1996; Miller & Matute, 1996). Similarly, geometric information may be immune from overshadowing in situations in which it is very salient, that is, instantiated with maximum power and minimum uncertainty.

Explaining the Development of Reorientation

Development of spatial reorientation capabilities may be conceptualized as the acquisition of the ability to encode relevant aspects of the environment with precision, and the learning of an optimal mix of weights to attach to these kinds of environmental information based on their past usefulness. By 18 months, the youngest age so far studied in the reorientation studies, children clearly have the ability to encode both geometric and featural information (Newcombe & Huttenlocher, 2000). But their acquisition of an optimal mix of information clearly consumes some time. In Figure 2, we see that the basic pattern appears to be the increased use of features, with geometry present from the start. (The developmental function looks different in large versus small rooms, both in timing of when features begin to be used and

in the abruptness of age-related change, and yet features do seem less powerful, in both contexts.) But this pattern of developmental change may not be inevitable; it may depend instead on the environments in which human children are currently raised.

We may imagine that human infants seek to orient and reorient themselves repeatedly, using whatever information is available. Some pieces of information might prove completely irrelevant. Other kinds of information may be very difficult to use due to the lack of specificity with which they can be encoded. For example, odors are difficult to localize, at least for our species. Over time, repeated experiences of this kind establish weightings of the likelihood of use and/or the extent of reliance on different kinds of information based on their certainty and their history of usefulness (or cue validity). In this view, geometry predominates early in human development because it has been experienced repeatedly in almost every environment that babies are in—parks and forests are infrequent experiences in modern society compared to cars and cribs and rooms. Features of the most useful kind—distal ones—are less frequently available in these enclosed environments. Further, when children are outside, they may not be allowed to roam as freely as would be necessary to engage their orientation skills and afford them the experiences of locating targets using distal features.

The most powerful evidence for this idea so far comes from a recent report showing that features overshadow geometry learning for wild-caught mountain chickadees, who have spent very little time in enclosed rectilinear environments (Gray, Bloomfield, Ferrey, Spetch & Sturdy, 2005). The chickadees *can* use geometry when it is the only information available, but they rely on it to a reduced extent than other (domesticated) organisms studied so far. Additional suggestive support for this idea comes from the fact that training history has been shown to affect reliance on features versus geometry (for pigeons, Kelly et al., 1998, but see also Kelly & Spetch, 2004; for humans, Kelly & Bischof, in press), and that, as we have seen, size of the surrounding environment affects the relative power of geometry and features.

Conclusion

The modularity-plus-language position presents a view in which an innate module remains unchanged in development, supplemented at some point by language. We have argued that this position

cannot account for the available data and have proposed an adaptive combination framework as an alternative. This framework is actually a general one that could be applied to many lines of development, both in the spatial domain and in other domains. The adaptive combination approach provides an account of why some sources of information are weighted more heavily than others in many lines of cognitive development, including the task of determining orientation, and suggests an account of development that stresses the acquisition of a dynamically changing mix of use of various information sources. Changes in this mix are likely to be importantly affected by children's history of spatial action, to be conditioned by their motor development and their socially-supported opportunities for exploration, and also to be affected by the characteristics of the environment with which they interact. Future research can explore specific hypotheses generated by this framework. In this chapter, we have identified some important themes, including systematic variation of the certainty and variability of different kinds of information, as well as their perceptual salience and their cue validity (or learning history). Cue validity can be investigated through within-experiment manipulation, or, excitingly, through altering rearing history (in research with non-human animals such as the mountain chickadee). Investigations along these lines have the promise of yielding detailed insights into the fine-grained process of developmental change.

Footnotes

¹ Interestingly, proponents of culturally-centered views of human development have often cited Spelke's arguments on this topic with approval while simultaneously arguing vociferously against nativism—a paradoxical juxtaposition (e.g., Levinson, 2003; see Newcombe, in press).

² Fodor (1983) agreed that a system could be domain-specific but unencapsulated. But he also argued that a domain-general system could, at least in theory, be encapsulated, noting that a system of this kind might “give some answer to any question; but it gives its answers off the top of its head—i.e., by reference to less than all the relevant information” (p. 104). However, he considered this possibility unlikely—as indeed it would seem to be!

³ To quote Fodor (1983) again, “if input analysis is modular....you might expect a kind of brain in which there is stable neural architecture associated with perception-and-language” (p. 118). With respect to the geometric module hypothesis, some neuroimaging work has in fact suggested that an area of the brain that has been termed the parahippocampal place area preferentially processes information about the shape of surrounding spaces (Epstein, DeYoe, Press, Rosen, & Kanwisher, 2001; Epstein, Graham, & Downing, 2003; Epstein & Kanwisher, 1998). However, other investigators disagree about this specialization (Maguire, Burgess, et al., 1998; Maguire, Frith, et al., 1998).

⁴ While one possible objection to the data on use of geometry when viewed from outside a space is that the geometric module only operates when one is within the space (Wang & Spelke, 2002), the fact that geometry is used at all in this situation suggests that what is happening is not the engagement versus lack of engagement of a module but rather a weakened reliance on, or probability of use of, an information source.

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Table 1

How Task Variations Affect the Age at Which Colored Walls as Well as Geometry Are Used to Reorient

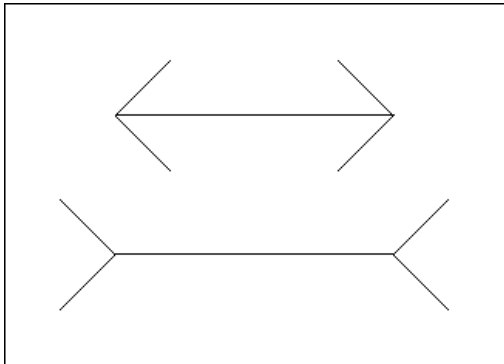
| | Colored Wall Distal? | Action Possible? | Target Adjacent to Space with Colored Wall? | Age at First Feature Use |
|------------------|-------------------------|------------------|--|--------------------------|
| Hermer-Spelke | No | No | Yes | 6 years |
| Learmonth et al. | Yes | Yes | Yes | 18 months |
| Study 1 | Yes | No | No | 6 years |
| Studies 2 & 3 | Yes | No | Yes | 4 years |

Figure Captions

Figure 1. The Muller-Lyer illusion. The horizontal lines are equal in length but they appear unequal.

Figure 2. Developmental changes in use of geometric and featural cues. From Cheng and Newcombe (2005).

Figure 3. When an observer is inside a space (as on the left) as opposed to viewing an enclosure from outside (as on the right), the geometry of the space is more distinct, as defined by angles of observation. From Huttenlocher and Vasilyeva (2003).



A. Geometric and Featural Cues

