Place and form: A case study in the disunity of core knowledge

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Abstract: Core knowledge theory holds that human cognition originates from a small set of innate modular systems, each of which is informationally encapsulated from the others. We subject this theory to scrutiny by critically examining one influential division within it: the distinction between an encapsulated core knowledge system for place (representing where things are) and an encapsulated core knowledge system for forms (representing object structure). Reviewing behavioral, developmental, and comparative evidence long taken to establish a double dissociation between these systems, we argue that the case for either system's encapsulation is considerably weaker, and the counterevidence more extensive, than typically acknowledged. In place of their strict encapsulation, we propose that place and form systems are better distinguished not by the information they have access to but perhaps by the proprietary algorithms that govern how they prioritize and process spatial information. More broadly, these results suggest that core knowledge does not constitute a single, architecturally uniform, psychological kind, but a heterogeneous family of systems that vary in the nature and degree of their modularity.

Keywords: Core knowledge, Geometry, Informational Encapsulation

One of the foremost goals of cognitive science is to understand the origins and organization of human knowledge. What knowledge is innate versus learned? Is knowledge acquired via flexible, domain-general learning mechanisms, or rigid, domain-specific ones? Are there distinct modules in the mind that map onto distinct domains of knowledge? If so, what are they?

Perhaps the most prominent attempt to systematically address such questions is the hypothesis that human knowledge originates from pre-wired domains of 'core' knowledge. In its latest rendition, the theory posits six domains, devoted to knowledge of objects, number, places, forms, agents, and social beings, respectively (Spelke, 2022; Spelke & Kinzler, 2007). Each domain maps onto its own distinct and specialized modular system, embodying innate and special-purpose knowledge therein. These modules are then seen to scaffold subsequent learning, enabling the characteristically flexible modes of thought found in appropriately enculturated adult humans. Putting these threads together, the core knowledge theory presents an elegant, unified theory of human knowledge that promises to account for both its origins and its development.

In the present treatment, we take a critical look at the core knowledge theory and the modular divisions it posits. Our inquiry is guided by a conviction that these modular divisions matter: Beyond the observation that core knowledge theory purports to provide a map for the development of *all* human knowledge, these divisions purport to explain otherwise puzzling dissociations in children's behavior as well as intuitions that persist into adulthood. Yet, we are skeptical that these modular divisions stand up to scrutiny, and to such an extent that they force a reconceptualization of both *what core knowledge is* and *how it is organized in the human mind*.

To frame our discussion, we focus on one specific modular division proposed by the core knowledge theory — the division between knowledge of places (roughly, knowledge of *where things are*) and forms (roughly, knowledge of *object structure*). We focus on this case study for several reasons. First, the domains of form and place both concern spatial and/or geometric knowledge. Core knowledge theory suggests that all geometric knowledge — and all the incredible technological, engineering, and mathematical human achievements that result from it — is built up from distinct geometric primitives that originate in these systems (Spelke & Lee, 2012). But since we are skeptical that a modular division between form and place withstands scrutiny, we worry that current formulations of the core knowledge theory have set theorizing about the development of spatial knowledge off on the wrong foot. Second, the proposed distinction between place and form representation is often treated as a theory of spatial cognition in its own right, independently of its bearing on the core knowledge hypothesis (e.g., Lee et al., 2012; Spelke et al., 2010). Throughout this paper, we refer to this theory as the *two-system view*. Despite the influence of the two-system view, there has been little attempt to critically evaluate the modular division it posits, and there has been scant attention paid to what an alternative framework might look like. It is these lacunae that the present paper fills. Third, spatial cognition is one of the best-studied topics in cognitive science. As such, it provides ample behavioral, computational, and neuroscientific evidence on which to adjudicate these issues and to explore the broader ramifications for the core knowledge hypothesis.

To clarify: While the distinction between form and place is but one modular division that proponents of the core knowledge theory posit, we believe that problems with this division raise concerns for the core knowledge theory more broadly. The aim of this paper is, thus, to articulate problems with the two-system view of spatial knowledge, and to explore the ramifications of this for our understanding of core knowledge as a distinctive psychological kind.

We proceed as follows. In §1, we clarify the core knowledge theory and the modularity of the systems it posits. In §2, we review the history of, and motivations for the two-system view, explaining how it naturally aligns with the core knowledge theory, thus construed. In §3, we critically evaluate the evidence that has been marshaled in support of the two-system view, arguing that we should doubt the modular dissociation between the form and place systems that core knowledge theorists posit. In §4, we discuss what a revised view of geometric and spatial knowledge might look like, provisionally introducing an alternative *diverging algorithms hypothesis*. Finally, in §5, we discuss where this leaves us with respect to core knowledge more broadly. We argue that the lessons gleaned from our discussion have broader implications for how core knowledge systems should be conceptualized: While some core knowledge domains have a genuinely modular architecture, we suggest that the a-modularity of core spatial knowledge undermines the grounds for thinking of core knowledge as an architecturally unified kind.

1 | Clarifying core knowledge

According to the core knowledge hypothesis, human thought originates from a small number of prescribed and innately hardwired domains of 'core' knowledge. Its latest rendition posits six such domains, devoted to knowledge of objects, number, places, forms, agents, and social beings, respectively (Spelke, 2022). While one might quibble with the term "knowledge" in this context, denying that these systems' representations are factive rather than heuristic (Carey, 2009; but see Davies, 2015, for helpful discussion), a key claim has been that these early emerging systems structure the "flexible skills and belief systems" (Spelke & Kinzler, 2007; p. 89) that are subsequently acquired throughout the lifespan. In this respect, the core knowledge hypothesis charts a middle ground between classical empiricism, which emphasizes purely domain-general system(s) of cognition and learning (Locke, 1689; Rumelhart & McClelland 1986), and evolutionary perspectives which have analogized the entire mind to a "Swiss army knife" (Pinker, 1994), comprising vast swathes of innate and highly specialized "mental organs" (Cosmides & Tooby, 1994; Pinker, 1997; Carruthers, 2006).

It should be acknowledged that the precise number of core knowledge domains is open to revision. Further domains might be discovered or — as we will argue here — proposed borders between established domains might erode under critical inspection. To even assess these possibilities, however, it is important to note that extant versions of the hypothesis regard each domain as distinct on account of being modular, in Fodor's (1983) sense of the term (Carey 2009; Spelke 2022).[1] Before turning to our central case study — the *two-system view of spatial knowledge* — it is worth clarifying exactly what this appeal to Fodorian modularity involves.

[1] Carey states that "the entities in core domains of knowledge are identified by modular innate perceptual-input devices" (2009, p. 11) and emphasizes Fodor's characterization of modules as informationally encapsulated systems (p. 10). Spelke is even more emphatic: She states that the systems and domains of core knowledge "are modular, in *all* the respects described by the philosopher and pioneering cognitive scientist Jerry Fodor in his Modularity of Mind" (2022, p. xx., *our emphasis*).

On Fodor's account, modules are computational mechanisms that can be characterized by their possession of nine properties, including *fast processing, fixed neural hardware,* and *domain specificity*. Chief amongst these is *informational encapsulation*, a property which serves as the "essence of a system's modularity" (Fodor, 1983; p. 71).[2] To wit: Classical computations rely on access to information or content to perform intelligent input-output functions. For instance, the visual system has been said to rely on information that light comes from a single source (above) when inferring shape from shading (Ramachandran 1988; Mamassian et al., 2002). Thus, the system takes information about shading as input and uses this to infer estimates of 3D shape as output in a quasi-rational manner (Rescorla, 2015). In saying that this process is underwritten by an informationally encapsulated module, Fodor proposes that while the visual system might utilize *this information* when estimating 3D shape, it lacks computational access to *other information*, even when this other information is located within the same organism's head and might be helpful in its operations. As such, the module is unable to use this other information to inform its computations, no matter how relevant it might be for its task functions. The module is *encapsulated* from this other information.

To clarify the proposal, Fodor (1985) characterizes encapsulated modules as systems which rely exclusively on information stored in private "proprietary databases". This allows for a graded notion of encapsulation: A module X can be regarded as *encapsulated* from a system Y *to the extent* that X's database fails to include information in Y's (Quilty-Dunn, 2019). As a result, an encapsulated module might share or be influenced by information used by other modular or non-modular systems (see also Coltheart, 1999). Indeed, Fodor emphasizes as much when taking the mechanism(s) of speech perception to serve as his exemplar of a modular system. To explain phonemic restoration effects, he urges that "on any remotely plausible account" [his own included] the language module will have access to the speaker's knowledge of the lexicon (1983, p. 77). Thus, Fodor was not opposed to — and, indeed, welcomed — the suggestion that a paradigmatically

[2] Philosophers of science have become increasingly wary of "essences" in their characterization of natural kinds (Khalidi 2013), particularly in the life sciences. Fodor's view was not classically essentialist, however. He took modularity to come in degrees, with the encapsulation of a system simply increasingly the likelihood that it possesses other markers of modularity, such as *speed* (c.f., Brooke-Wilson 2023) and *domain specificity* (c.f., Margolis & Laurence 2023). Plausibly, then, encapsulation was viewed as more like a sustaining mechanism in a homeostatic property cluster, with Fodor's terminology reflecting the fact that he was writing ~ten years before the distinction between essentialism and property clusters was clearly formulated in the philosophy of biology (Boyd 1991; 1999).

modular and encapsulated system might have access to the speaker's knowledge (in this case, knowledge of words) which is accessed and used in thought (as when we, e.g., think about word meanings and formulate sentences). What is critical is that encapsulation remains *architecturally prescribed*: It marks a fixed constraint on what information/content *can* be synchronically accessed by the system and (hence) used to inform its computations. Thus, the claim is not simply that encapsulated systems neglect to consider certain information in their computational procedures (as when we neglect our beliefs about star signs and clownfish while deciding which hummus to buy at the supermarket). Rather, the claim is that there is an architectural boundary which determines what information *can* be accessed or used by the cognitive mechanisms involved. This is how the visual system's encapsulation from background beliefs offers to explain why known illusions persist. Even when you believe things that should rationally alter your visual system's analyses, and even when you reflect on these, your visual system's encapsulation implies that it lacks access to such beliefs. This renders your beliefs incapable of informing or altering the system's input-output function and reorganizing your percept accordingly when sensory inputs are held fixed. By contrast, your beliefs about star signs are plainly not encapsulated from your hummus-related-shopping-decisions. While we might neglect to consider such beliefs, they are accessible and can be brought to bear on the decision-making process, at least when their relevance becomes salient (e.g., if we learn that Libras like their hummus creamy and that we are shopping for the 36 Libras attending dinner).

Thus, when proponents of the core knowledge hypothesis allude to Fodorian modularity, they mean to posit an encapsulated module that corresponds to each domain of core knowledge. By suggesting that there are six such modules (Spelke, 2022; Spelke & Kinzler, 2007), Spelke commits to each of these modules being individuated by their possession of a unique and architecturally prescribed proprietary knowledge database (see also Carey, 2009). Following Fodor, these databases delimit what information *can* be accessed by each system in the performance of its domain-specific input-output function. Accordingly, Spelke and other proponents of the core knowledge theory find evidence for distinct modules underlying small and large numerical discriminations (Feigenson et al., 2004), the representation of agency (Spelke et al., 1995), object tracking (Spelke, 1990), and the spatial representation of forms and places (e.g., Lee et al., 2012; Spelke et al., 2010). In each case, these assessments are premised on the conjecture that each system differs in the information that it accesses and produces. The basic theoretical move, to be highlighted in Section 2 (and scrutinized in Section 3), is that the best explanation for *why* these systems differ with respect to the information that they access in their computations is that they differ in the information that they *can* access in their operations — that the architecturally prescribed encapsulation of the systems dictates this.

2 | A "two-system" view of spatial knowledge

Having introduced Fodorian modularity, let us now consider how it plays out in the context of our central case-study: the two-system view of spatial knowledge.

2.1 Historical precursors to the "two-system" view

Early motivations for the two-system view can be traced to Cheng (1986), whose pioneering work led him to posit a *geometric module* — i.e., a domain-specific navigation system that is encapsulated from non-geometric information. This conjecture was motivated by Cheng's empirical results. In a series of celebrated experiments, Cheng placed food-deprived rats in the center of rectangular environments in which walls were marked by non-geometric features (e.g., colors, spots, or stripes; see Figure 1A) that they ably discriminate in other contexts (see, e.g., Julian et al., 2015). Food would then be hidden in one of the corners, and the rats were trained to search for this at the appropriate location, following the same trajectory through the room on each occasion. In subsequent test trials, the rats were returned to the center of the rectangular environment, but this time disoriented, such that they would need to reorient themselves within the environment to locate the target food item.

The rectangular environments were constructed such that if rats freely integrated non-geometric information (the colors, spots, and stripes on the walls) with geometric information (concerning the angles, lengths, or distances of/between the walls) whilst reorienting in the room, they would have no trouble selecting the correct corner when locating the food. Likewise, if the rats relied only on *non-geometric* information (e.g., if they encoded the location relative to a striped wall), they would search only near the corresponding learned feature. By contrast, if rats relied only on *geometric* information, they would search equally often at the correct corner as well as the *opposite* corner since these were geometrically equivalent. The guiding thought was that systematic errors made by the rats would reveal the information they had used to reorient themselves within the rectangular environments employed.

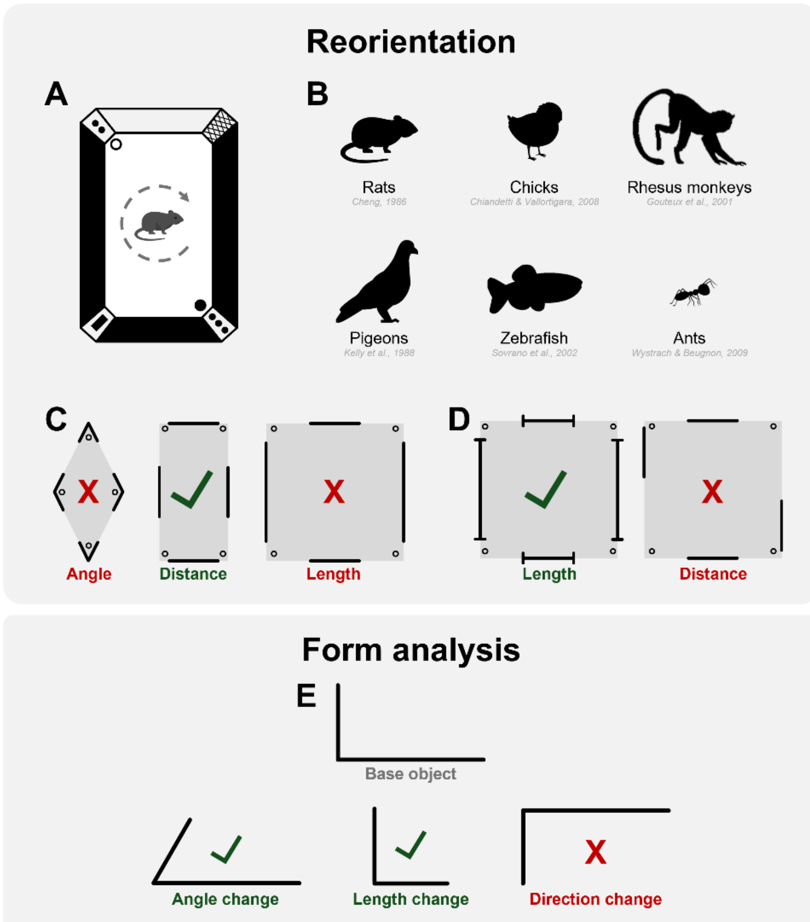

Figure 1. Reorientation and form analysis tasks. (A) Geometric and non-geometric information in the original reorientation task, as seen from above (Cheng, 1986). The room's rectangular shape creates two rotationally equivalent and diagonally opposite corners. The filled circle indicates the desired target, while the open circle indicates the geometrically (rotationally) equivalent corner. The patterns on the walls indicate non-geometric features of the room, which in principle could be used by the rats. (B) Relevant findings across species show the same pattern of errors in the reorientation tasks. (C) Conditions from Lee and colleagues (2012) in the reorientation task with 2-year-olds. Starting from left to right, each scheme indicates a tested feature: angle, distance, and length. The symbol "✓" indicates evidence of using the cue, and "X" indicates evidence of not using the cue. (D) Conditions from Yousif & Lourenco (2017) in the reorientation task with young children. In the left scheme, perpendicular "appendages" were added to the end of each wall, and young children use them to reorient. In the right scheme, distance was manipulated while maintaining the overall square shape of the environment. Although the two-system framework predicts that children should use distance in this condition, they were unable to do so. (E) A simple form analysis task from Izard and Spelke (2009) in which children were tasked with identifying the odd-one-out given various geometric changes. They detected angle and length, but not direction changes.

Where, then, did the rats search? Cheng found that they searched equally often at the correct corner (i.e., where the reward was actually hidden) and its geometric equivalent (i.e., the corner directly opposite where the reward was hidden). This indicated that (a) the rats had relied on geometric information of the room to reorient themselves, and that (b) the rats hadn't integrated this geometric information with non-geometric information, which would have otherwise disambiguated the target location.

To make sense of these results, Cheng conjectured that the rats had relied on a 'geometric module' to reorient in space. More specifically, he conjectured that they relied on a cognitive module with computational access to geometric information, which is informationally encapsulated from non-geometric information, rendering this non-geometric information *inaccessible* to the system guiding reorientation behavior. Sometimes it is objected that this hypothesis does "little more than label the findings" Cheng reported; that it merely redescribes the observation that rats utilized geometric information while neglecting to integrate non-geometric cues (Butterfill, 2007, p. 453). We disagree. The postulation of a geometric module is a substantive conjecture that goes beyond Cheng's results, in ways that offer to genuinely explicate them.

To illustrate, suppose we accept results (a) and (b) and thereby accept that rats' reorientation behavior is responsive to geometric information and insensitive to non-geometric information. Cheng's modular hypothesis offers to explain why this might be by appealing to the architecture of the mechanisms involved. Boldly stated, it explains a pattern of observed behavior by appealing to a hypothesis at a lower (algorithmic) level of analysis. Mirroring modular explanations for the recalcitrance of known illusions, described in Section 1, Cheng's theoretical gambit was this: He proposed that *the best explanation* for why rats failed to utilize non-geometric information in his reorientation studies is that the system responsible for reorientation lacks computational access to non-geometric content. That is, the system is *encapsulated* from non-geometric content, as dictated by its architecturally prescribed proprietary database.

Crucially, Cheng's (1986) modular hypothesis is no foregone conclusion. In principle, we could make sense of Cheng's results in other ways, supposing that the system(s) involved did have access to non-geometric content but failed to utilize this during reorientation for other reasons. This might be akin to the way that we sometimes use heuristics to solve complex reasoning problems and thereby fail to integrate things that — on reflection — we know to be relevant (Simon 1955; Tversky & Kahneman 1974). In these cases, it's not that our faculty of reason *cannot* access such knowledge. Such knowledge may not be accessed when cognitive shortcuts are available, perhaps as a means of conserving valuable cognitive resources. Either way, it remains *accessible* to our faculty of reason. For, if its relevance is pointed out to us, we can freely integrate it into our thinking, hence why we are often able to appreciate the error of our ways once this becomes apparent.

Nevertheless: While Cheng's appeal to modularity is no foregone conclusion, it was certainly striking that the rats tested in his studies appeared to systematically neglect information that strikes us (mature adult humans) as transparently relevant to the reorientation procedure these (food-deprived) creatures were motivated to perform. For this reason, the proposed encapsulation of their reorientation system deserved to be taken seriously as a possible explanation for the observed results.

2.2 From rats to children

Forty years on, Cheng's work remains a cornerstone of the field. In its wake, numerous studies were conducted with other animals, yielding analogous results (see Figure 1B). Chicks (Chiandetti & Vallortigara, 2007), zebrafish (Lee et al., 2013), non-human primates (Gouteux et al., 2001), and ants (Wystrach & Beugnon, 2009) have all been found to search at the correct corner of a room and its rotational equivalent with equal frequency, neglecting to use non-geometric information. Insofar as this is indicative of a "geometric module," which is encapsulated from non-geometric information, the module is often assumed to be evolutionarily ancient and widespread in nature.[3]

Perhaps the most striking of these results came almost a decade after Cheng's original study, when Hermer and Spelke (1994, 1996) adapted Cheng's reorientation paradigm to test young human children's navigational abilities (18-24 months). Using a setup that closely mirrored Cheng's, Hermer and Spelke tested whether human adults and children would integrate featural (non-geometric) information with geometric information when

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[3] An alternative possibility is that its emergence in distantly related species reflects a process of convergent evolution (compare: Nieder 2021), where evolution has selected for some such system many times over; perhaps because the prioritization of geometric information reflects an optimal navigation strategy in natural environments where featural content (e.g., the color of decaying leaves) is often more changeable than the gross geometric structure of the landscape (e.g., Gallistel 1990, ch.5).

reorienting. Human adults were not fooled: Unsurprisingly, they flexibly reoriented using both geometric and non-geometric information. More surprisingly, however, Hermer and Spelke found that 18- to 24-month-old children failed to integrate featural information with geometric information; like rats, young children seemed to reorient based on geometric information alone.

Why do children fail where adults succeed? Hermer and Spelke argued that humans, just like rats, chicks, and zebrafish, have a geometric module that supports spatial representation and reorientation, where this system is encapsulated from non-geometric information throughout the lifespan. Unlike other species, however, they observed that appropriately enculturated humans develop linguistic abilities. Hermer and Spelke thereby conjectured that these linguistic abilities enable the outputs of distinct modular systems to be combined across otherwise distinct cognitive domains in adults, thus enabling geometric and non-geometric cues to be reasoned with in tandem (see also Spelke, 2003).

What is striking about this latter conjecture – for our purposes – is that it effectively doubles down on the proposed encapsulation of the faculties involved: Without language, Hermer and Spelke suggest that the geometric module is incapable of accessing contents processed by other systems, nor of even combining the outputs of these systems with those of others that "present the world to thought" (Fodor 1983, p. 40).[4] Hence, the geometric module is considered unavoidably encapsulated from the featural content represented by sensory modules. Furthermore, it is conjectured that it is only with the maturation of language that humans acquire an ability to combine the outputs of this system with those produced by others (as when we think, e.g., *LEFT OF THE LONG RED WALL*). These conjectures ultimately laid the foundation for Spelke's postulation of a modular, evolutionarily ancient place system, for reorientation and navigation, which remains a foundation of the core knowledge hypothesis today (Spelke, 2022).

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[4] While we are skeptical, the hypothesis that language enables the outputs of modules to be combined is quite different from the claim that language enables these systems' encapsulation to be violated. The output of a module is a representation that the module produces and makes accessible to other systems of the mind, with or without the aid of language. By contrast, encapsulation pertains to a restriction on the information, content or representations that are utilized in its production of those outputs. For discussion of this issue, see Clarke (2021).

2.3 From historical precursors to the contemporary proposal

The preceding discussion sketches some important historical precursors to the two-system view. However, the contemporary proposal did not emerge until 2012, when Lee, Sovrano, and Spelke found that children would not use *all* geometric information in reorientation paradigms. Using enclosures with walls of differing lengths, forming different angles, and/or that were placed different distances apart (see Figure 1C), Lee et al. reported that children would reorient exclusively based on the distances and directions between walls (i.e., sense information) and that they would *not* use information concerning the lengths of these walls nor the angles between them. While we will see that these findings have been challenged (see Lourenco et al., 2009; Yousif & Lourenco, 2017), they underpin Spelke's contemporary view on spatial representation, according to which we must differentiate two modular systems of core knowledge: a *place* module for representing and navigating large-scale spaces and a *form* module for representing the spatial structure of objects. It is this modular division which constitutes the two-system view of spatial knowledge.

The key motivation for this modular division was a proposed double dissociation between place and form analysis. Building on Lee et al.'s results, the two-system hypothesis posits that children use distance and direction (sense) cues while ignoring length and angle cues in reorientation paradigms. Proponents of the two-system view take this to refine the postulation of a geometric module, noted above; rather than simply remaining encapsulated from non-geometric content, *writ large*, they take this to show that the place system is encapsulated from certain geometric contents as well, namely length and angle, and that it must rely entirely on the dedicated sense content it has access to within its proprietary database.

This is then contrasted with children's recognition of objects and 2D shapes (Lee & Spelke 2010), where an orthogonal collection of geometric cues is prioritized and used (Dehaene et al., 2006; Izard et al., 2011; Schwartz & Day, 1979). For instance, Izard and Spelke (2009) tasked young children with identifying which of six objects deviated from the others geometrically. Throughout this experiment, all the objects used were two-dimensional shapes with an L-shaped structure (see Figure 1E). Where they differed was simply in (a) the lengths of the lines that these L-shapes comprised, (b) the angle between these lines, or in (c) the direction of the lines with respect to each other (e.g., whether the target L-shape was a mirror image of the others).

During testing, a clear pattern emerged: All age groups ably identified deviant shapes/objects when these were distinguished by variation in the lengths of the lines they comprised or in the angles between them — in other words, it proved relatively easy to distinguish the *odd-one-out* when it was distinguished by the very geometric features that are neglected in reorientation paradigms. Meanwhile, participants proved relatively *in*sensitive to direction information of a sort that *is* used in reorientation paradigms. As a result, they were poor at recognizing deviant forms which were distinguished by being mirror images of other items. In fact, the studies revealed that differences in angle and length routinely interfered with one another, such that on trials where the target shape was distinguished by its unique angle, varying the line lengths across the other objects served as a distraction that adversely affected participants' abilities to detect the oddly-angled target; by contrast variation in sense/direction content had no such effect, suggesting that it was not even considered. Summarizing these results, Spelke, Lee, and Izard (2010) conclude that in object recognition, "sense is difficult to detect and easy to ignore" despite sense content dominating performance in reorientation studies (p. 872).

These latter findings hence motivated the postulation of a second, distinct and autonomous, module for the representation of forms — a module that has access to specific geometric information, like angle and length, while remaining encapsulated from direction information that is accessible to the place system used in reorientation. Since these results mirrored previous findings, where adults from communities that lack relevant linguistic labels show analogous dissociations to the children described above (Dehaene et al., 2006), Spelke, Lee and Izard (2010) take this to further evince Spelke's hypothesis that language is needed to combine the outputs of distinct and encapsulated core knowledge systems, like those for *form* and *place*.

Summing up: The two-system view of spatial knowledge posits two geometric modules (see also Huang & Spelke, 2015). First, there is a *place* module that facilitates reorientation behavior. Crucially, this system has access to information concerning "absolute distance and sense [i.e., direction] … but not relative length or angle" on account of its encapsulation from the latter. Second, there is a module for *form analysis* that "does the reverse", making free and flexible use of length and angle information while remaining encapsulated from sense information (Spelke & Lee 2012; p. 2789). In both cases, the proposed modularity of the systems is a weighty conjecture that goes beyond observed patterns of behavior. It is a theoretical conjecture, pitched at an algorithmic level of analysis (Marr, 1982), which offers to explain why children behave as they do in the studies described, responding to and making use *of* orthogonal geometric cues in reorientation paradigms and studies of visual form analysis, respectively. As articulated above, the guiding assumption is that the best explanation for these diverging patterns of cue usage in these studies is that the observed behaviors are guided by distinct and autonomous modules, each relying on access to information stored within an independent proprietary database. Critically, this leaves either system *encapsulated* from the geometric information that is made use of by the other. It is only with the aid of extraneous resources — most notably, *language* (Spelke 2003; Hermer & Spelke 1994) — that the outputs of these modules can be combined or even considered concurrently with content from other systems and modules.

Before moving on, it is worth flagging that proponents of the two-system view sometimes take their position to be further supported by results from cognitive neuroscience. To this end, they note that (most) scene regions of the brain (the occipital place area [OPA] and retrosplenial cortex [RSC], but *not* parahippocampal place area [PPA]) *are* sensitive to left-right information, whereas the posterior fusiform sulcus, an object region, is not (Dilks et al., 2011). More recent work has shown that the same scene regions that respond to sense information also respond to egocentric distance information (Persichetti & Dilks, 2016). And, interestingly, the scene region that does not respond to sense and distance information, the PPA, *is* sensitive to the geometric properties associated with object recognition — length and angle (Dillon et al., 2018). Since these dissociations appear to mirror the behavioral dissociations which motivate the two-system view's modular division between place and form systems, these findings have led to the suggestion that, within the scene network, there are dissociable neural systems for recognizing scenes and navigating through them (Persichetti & Dilks, 2018). While it is unclear to us if or how such neuroimaging evidence bears upon the hypothesis that the form and place systems are encapsulated modules, we flag this because such evidence is sometimes cited as strong evidence in favor of the two-system framework (Spelke, 2022), perhaps owing to the idea that if each of the systems it posits are implemented in independent neural hardware this is suggestive of the view that independent data structures are guiding their computations. Whether or not this inference is warranted, it is widely supposed that such neural data is consistent with, and perhaps congenial to, the two-system view, as it is articulated in the literature. We return to these points below.

3 | Problems with the two-system view

The two-system view paints a pretty picture: It posits two modules, one for the spaces we *navigate*; another for the objects we *recognize* and *manipulate*. One module is for *places*; the other is for *forms*. Conveniently, Euclidean properties of distance, length, angle, and direction fit neatly into this framework: The former system, *the place module*, traffics in distance and direction, while the latter system for processing objects, *the form module*, traffics in length and angle. Moreover, it is hypothesized that the reason for this clean dissociation is that each system is encapsulated from the geometric representations that are made use of by the other; that it is only through the deployment of further cognitive resources (namely, *language*) that the outputs of these encapsulated modules can be combined, as when mature and enculturated adult humans reason about objects that are individuated by their *shape, color, and location* and thereby reorient in ways that infants and non-human animals cannot (e.g., Hermer & Spelke, 1994).

At any rate, that is the theory. We believe it to be mistaken. The current section highlights reasons to be skeptical of the modular division that the two-system view proposes, thereby motivating the development of our novel framework within which to understand pre-linguistic spatial cognition.

Concern 1: Encapsulation from non-geometric content

To begin our critique, consider again Cheng's (1986) postulation of a 'geometric' module. While this posit has been superseded by the postulation of two distinct geometric modules, for form and place respectively, Cheng's hypothesis forms the bedrock on which this more contemporary view is built.

To remind the reader: Cheng found that rats — and subsequently many other creatures, including pre-linguistic infants (Hermer & Spelke 1994; 1996) — neglect to use salient non-geometric information, such as colors, spots, or stripes, when reorienting. Cheng's modular hypothesis was then introduced to make sense of these results, submitting that reorientation is facilitated by a system which is encapsulated from non-geometric information. Thus, it was conjectured that rats and other creatures fail to utilize non-geometric cues in their reorientation behavior because the underlying system that enables their reorientation is architecturally prevented from accessing this information; that such cues are systematically inaccessible to the underlying system involved. As such, they *cannot be accessed by the system*; the architecture of the system prevents this.

Subsequent formulations of the two-system view build upon Cheng's modular hypothesis, submitting that he did not go far enough. On these more recent proposals, the place module that enables reorientation remains encapsulated from non-geometric cues; however, it is now deemed to be encapsulated from certain geometric features as well (namely, distance and angle). Hence, it is suggestive of problems with the two-system hypothesis and its underlying foundations, that Cheng, himself, later came to reject his prior postulation of a geometric module. Cheng and Newcombe (2005) argued that although many species often neglect to utilize non-geometric information for reorientation, the evidence no longer supports the existence of an encapsulated, modular system. These concerns were then crystalized when Twyman and Newcombe (2010) offered "*Five Reasons to Doubt the Existence of a Geometric Module*". Of those five reasons, we find two particularly compelling, especially when attention is paid to the central commitments and virtues that Fodorian modularity was expected to have in this context.

Firstly, notice that if reorientation behavior depends on a purely geometric module — which is literally encapsulated from non-geometric information — it would be puzzling to find that creatures' failure to use non-geometric information is fragile, and depends heavily on the parameters of the experiment. After all, we take it that the basic reason to posit a geometric module is that this offers to explain why rats and children *don't* (ever!) incorporate featural content when reorienting; that, by hypothesis, this is a result of the fact that the underlying system simply *cannot* access the relevant representations, no matter how helpful these might be. This is akin to the way that encapsulation offers to explain why known illusions persist; even when one reflects on their knowledge of the illusion, and the relevance of this knowledge to our visual system's analyses, it is (by hypothesis) inaccessible to the system and, thus, strictly incapable of altering or informing its conclusions, no matter how helpful or salient it might be.

The trouble is: The failure to use non-geometric cues in reorientation paradigms is, in fact, remarkably fragile. When researchers manipulate the size of the room used in reorientation experiments, say, the failure to integrate non-geometric information often disappears. Specifically, in large enclosures, children (Learmonth et al., 2002), human adults (Ratliff & Newcombe, 2008), and non-human species (Sovrano & Vallortigara, 2006) reorient using non-geometric features. While one might reply that some core knowledge modules only operate within certain parameters or ranges and that – outside of these – other mechanisms must be engaged (see Feigenson et al. 2004; Clarke forthcoming), the abovementioned discrepancies are surprising since it is typically claimed that insofar as a geometric place module exists, it functions to represent large-scale spaces specifically (e.g., Spelke, Lee, and Izard 2010). Thus, these findings suggest that featural information is not strictly inaccessible to the place system (and hence encapsulated from it), and that such information can become integrated into the system's computations in precisely those situations where the system is expected to operate. This is so, even if featural information fails to be used or prioritized in other contexts.

To address these concerns, Shusterman and Spelke (2005) maintain that while the place module lacks access to non-geometric information, and remains fully encapsulated from featural information, domain-general associative processes can sometimes enable organisms to proceed as if reorientation computations are being performed over featural representations. On this proposal, true reorientation still requires young children to employ a geometric place module that proceeds independently of non-geometric content. Nevertheless, associative processes can sometimes enable them to associate specific features with responses, targets, or outcomes, thereby allowing these features to serve as "beacons" which can be directly approached. In saying this, Shusterman and Spelke stress that these associative processes do not facilitate genuine reorientation computations since they simply encode for one target and fail to license further inferences about directional or sense relations; they *only* enable creatures to directly approach target locations. Nevertheless, when rooms are made larger – and featural cues are scaled accordingly, as they were in the abovementioned studies – it is proposed that children and other creatures may succeed in locating a target by simply associating it with a salient feature and approaching this, thereby bypassing the distinctive signature limitations of the geometric place module entirely.

We find this unconvincing. To our minds, Shusterman and Spelke's response is either falsified by subsequent results, or it accommodates these but inadvertently leaves the postulation of an encapsulated place module unmotivated.

Consider that, in another study, Newcombe and colleagues (2010) found that 3- and 5-year-olds *could* use featural information to locate a toy duck, making flexible inferences when reorienting in an octagonal space comprising two sets of four geometrically equivalent corners. Under these conditions, children were able to use a blue corner to selectively reorient towards one of three geometrically equivalent white corners. To accomplish this, they needed to represent and utilize a blue feature, attribute this to a given corner, and then use this stored information to conceptualize and organize the space as a whole, combining this featural content with geometric information such that identically colored white corners could be distinguished by their spatial relationship to the feature. Putting the point explicitly: The children could not have completed this task by simply associating BLUE CORNER with TOY DUCK since the blue corner was not the target location they selectively approached. They also could not have completed the task by simply associating the geometric and non-geometric features of the all-white target corner with TOY DUCK since doing so would have led them to approach the target corner and the other white and geometrically equivalent corners with equal likelihood. Rather, it appears that they represented BLUE, attributed this to a specific corner, and then used this attribution to structure and distinguish the target corner from otherwise identical white angled corners within the octagonal space — representing that (e.g.) the target corner is *the first corner to the left of the blue corner that has certain geometric properties*.

How might Shusterman and Spelke explain this further result? It seems that they must make one of two concessions, neither of which appears palatable on their association-based account. One option would be for them to concede that, in this more recent study, featural content really was being accessed by the geometric place module, conceding that this module is not strictly encapsulated from featural information after all. In other words, this first option would have them abandon the full-blown encapsulation of the place module from non-geometric content. While this might be welcomed by those who stress that modularity comes in degrees, and who thereby hold that full-blown encapsulation is simply an ideal (Coltheart, 1999), it is important to note that this amounts to more than a gentle weakening of the view. On the contrary: It appears to rob the postulation of a geometric place module of its explanatory power. For once it is allowed that the place module can *sometimes* access non-geometric content, it is no longer clear how positing a geometric place module is meant to explain children's and rats' failure to integrate featural information in classic reorientation paradigms. Why don't they make use of featural information hereabouts if, strictly speaking, this information is accessible to the system? Indeed, it is no longer clear what empirical predictions fall out of the view. Without some principled explanation for patterns of non-geometric feature integration, the postulation of a geometric place module simply predicts that children and rats will neglect to use geometric information in reorientation studies — except when they don't.

Absent some such explanation, Shusterman and Spelke might therefore favor a second option when addressing these concerns. Where the first option would have them weaken their hypothesis that there is a genuinely encapsulated geometric place module, this second option would instead have them reformulate their understanding of the associative mechanisms that allow this system's limitations to be bypassed. For where Shusterman and Spelke (2005) emphasize that such associative mechanisms merely enable children to associate features with target locations, such that children can find these by directly approaching the features in question, it might be replied that Newcombe and colleagues' results simply show that this underplays the flexibility of the associations involved: In reality, Newcombe and colleagues have shown us that these are sufficiently flexible that they can support the appearance of sophisticated navigational reasoning, enabling associations to be formed between target locations and complex nexuses of geometric and featural cues, such that a child might treat (e.g.) *the white corner with such and such an angle, that is one left of the blue corner* as a beacon. The trouble with this second proposal is that if such rich associative processes are available to young children, it is unclear what benefit a more restricted place system continues to afford, or why these associative processes fail to save the day in the studies that motivated positing a geometric module to begin with. If, for instance, an association can be formed that enables children to treat such complex nexuses of features as beacons, it is unclear why children tested by Hermer and Spelke's (1994; 1996) were unable to form the much simpler associations that needed between (e.g.) BLUE STRIPES and CRACKERS such that they would routinely disambiguate the geometrically equivalent corners.

Either way, it seems that Newcombe et al.'s (2010) results problematize the postulation of a geometric place module that is encapsulated from non-geometric content. At best, they force a weakening of the hypothesis that robs it of explanatory power; at worst, they blunt the very reasons we had for taking the hypothesis seriously.

Of course, we shouldn't abandon an influential theory of spatial cognition based on one (or two) anomalous findings. However, these are not isolated worries. A second concern is that training is found to improve children's ability to combine geometric and non-geometric content in reorientation studies. Twyman and colleagues (2007) illustrated this, showing that, after a small number of training trials, young children (four- and five-year-olds) were able to flexibly integrate geometric and non-geometric information in small enclosures (see also Lourenco & Cabrera, 2015). Again, this looks antithetical to the claim that non-geometric information is strictly inaccessible to the system utilized. In this study, children seemed to be at least *capable* of integrating and accessing geometric and non-geometric information for the purposes of reorientation, even if they do not always do so spontaneously.

These points should be interpreted with caution: It might be replied that four- and five-year-olds have begun to acquire language, and that this enables the cross-modular integration of outputs that Spelke and Hermer posit. Nevertheless, it is worth noting that this is the same age group that was tested by Lee et al. (2006) and marshalled in support of the conjecture that reorientation proceeds independently of certain geometric cues during early childhood. In any case, our point is not that these results are utterly decisive. We simply note that since young children have the capacity to integrate geometric and non-geometric information when reorienting, following brief periods of training; that a satisfactory account of their behavior ought to explain such facts; that appeals to encapsulation are unhelpful in this regard; and that the plausibility of a viable explanation for their behavior ought to take into account whether its adoption inadvertently blunts the empirical motivations we had for taking a geometric module seriously at the outset. Hence, our point is really that the evidence for a geometric module has proved to be far messier than initially envisaged, and had this messiness been known earlier, the postulation of a geometric module would never have looked particularly parsimonious or attractive.

Proponents of the two-system view might shrug off these concerns. It might be replied that the modular dissociation between a form and place module is not strictly dependent on either system's encapsulation from non-geometric content; what is vital is simply that each of these systems is encapsulated from *orthogonal* geometric contents. After all, this orthogonality generates the double dissociations that motivate positing independent modules for form and place, regardless of whether these systems access non-geometric content. The trouble is: As we will now see, the arguments for thinking these systems are encapsulated from orthogonal geometric contents prove similarly problematic to those regarding the systems' encapsulation from non-geometric contents.

Concern 2: Encapsulation from orthogonal geometric cues

In early formulations of the two-system framework, Spelke considered not four, but three, Euclidean properties: direction (or sense), angle, and distance — the latter of which was used interchangeably with length (Spelke et al., 2010). Distance and length were later separated following admirably thorough investigations of children's reorientation behavior by Lee, Sovrano, and Spelke (2012). In this work, distance was described as the spatial extent between two objects, whereas length was described as the spatial extent between two points along a single object. To recap: Lee and colleagues found that children would reorient based on the distances between walls but not on the lengths of the walls (see Figure 1C). Fodorian modularity was then deployed to make sense of this division, appealing to the idea that if there are fixed constraints on the cues that each system can access in its computations, this might explain such dissociations. For, if the place module cannot access length contents (if it is *encapsulated* from this information), then such content is simply not positioned to alter the system's input-output function, with analogous points holding of other core knowledge systems, like the form module.

There are, however, exceptions to the sharp dissociation between these systems' use of length/angle and distance/direction, respectively. Borrowing the general design from Lee and colleagues (2012), Yousif and Lourenco (2017) showed that preschool-aged children (1) *can* use length information to reorient under certain conditions (e.g., when the lengths are made more salient by adding 'appendages' to the end of each wall segment), and also that they (2) *will not* use distance information to reorient under other conditions (e.g., when the 'global shape' of the environment forms a square which lacks meaningful geometric information because all four corners and walls are geometrically identical; see Figure 1D).

These findings are important for two reasons. First, they suggest that the systems underlying reorientation have access to more spatial information than merely distance and direction cues, including that which the module is hypothesized to be encapsulated from. Of course, adding appendages to the wall segments plausibly makes length easier to notice, and hence more salient to subjects in reorientation paradigms. But, if the place system were genuinely encapsulated from length information, salience should not matter (compare, again, the fact that the salience of a known illusion makes no difference to its persistence). Second, these findings offer a way to understand all the reorientation results without appealing to specific geometric features (but instead by appealing to the 'global shape of the environment'), suggesting that, ultimately, children navigate based on salient properties of the space and not merely specific geometric dimensions.

To reiterate why all of this matters vis a vis the broader claim about modularity: In much the same way that Fodorians appeal to the encapsulation of the visual system from the organism's explicit beliefs to make sense of why the lines of the Muller-Lyer continue to look different lengths even when we get out our tape measure, confirm that they are not, and reflect on this fact, a system that is similarly encapsulated from length information should not to be able to access or make use of this information no matter how salient it becomes. The architecture of the system would preclude this.

Quite different concerns might be raised regarding the form module's proposed encapsulation from distance and direction. While encapsulation from distance and direction is posited to explain why forms and mirrored forms often fail to be distinguished, it has long been understood that sense invariance for objects may not be so much about the mental systems that support object recognition but more about the objects themselves. Bornstein and colleagues (1978) note that "the confusion of mirror images is not a 'confusion' but an adaptive mode of processing visual information. In the natural world, the only mirror images that ever occur are aspects of the same thing and therefore need not be distinguished" (p. 32). In a paper beautifully (sub-)titled, "Reflections on mirror images", Walsh (1996) points out that "it is not every day that one is troubled by being required to remember the orientation of a painting" (p. 1081). Dilks and colleagues (2011), writing about these mirror confusions, note that they may arise simply "because many objects are vertically symmetric" (p. 11305).

This is much less often the case for navigated spaces, of course. Usually, turning left versus turning right is consequential. In practice, this means if we *really* wanted to understand whether children (or adults, for that matter) are equally sensitive to sense information in objects versus scenes, we would have to create a special set of objects and scenes for which that sense information was equally diagnostic. While we are confident such a stimulus set could be made in principle, we are not sure that such a thing has ever been tested. Indeed, this is pressing since evaluating the use of sense information in form analysis has long been argued to rely on processes of mental rotation (Shepard & Metzler, 1971), that are both effortful and demanding of working memory (Hyun & Luck, 2007). The effortful and demanding nature of these processes alone might suffice to explain why sense information is neglected in form analysis (compare Westra, 2017, and Carruthers, 2015). In any case, what would need to be shown is not simply that children have a preference or tendency to neglect certain cues, but that the neglected cues *cannot* feature in their analysis of object forms, no matter how salient they become, and no matter how relevant they are in the system's computations. Thus, we are not sure that there is sufficient evidence to justify the claim that children (or adults!) selectively neglect sense information in the context of form analysis, at least not in ways that would motivate thinking that such content is strictly inaccessible to the mechanisms or systems involved.

Positive evidence for geometric cue combinations

There are many other independent pockets of evidence that cast doubt on how cleanly dissociable the geometric cues involved in form and place analysis prove to be. For example, it has been shown that adults represent locations in both small-scale spaces (Yousif & Keil, 2021; Yousif et al., 2024; see also Yousif, 2022) and in large-scale spaces (Chen et al., 2025) using *polar coordinates* by default. Importantly, polar coordinates convey angle and distance information — cues that are typically separated in the two-system view. On the two-system view, it is unclear why angle and distance information would become spontaneously integrated as part of a default mode of spatial representation, given that the dissociations that motivate two-system view are said to persist into adulthood (as is the case with sense invariance of objects, for instance).

Then there is the fact that both small-scale objects and large-scale navigable spaces are said to be represented with their topological structure first and foremost, with metric information encoded secondarily (Yousif & Brannon, 2024, 2025; Yousif et al., 2026). Indeed, adults make the same kind of systematic errors that result from this in drawing both navigable spaces (Byrne, 1979; Moar & Bower, 1983) and simple 2D forms (Kittur et al., 2026) from memory, suggesting that common representations are employed. There is also reason to believe that this topological sensitivity is early developing and stable throughout the lifespan, with children as young as four years old matching objects with respect to their topology in a manner that is almost identical to the matching behavior of adults (Yousif et al., 2025).

Regardless of whether we take this evidence to meaningfully undermine the two-system view, they point to the fact that there are various spatial representations (e.g., coordinate representations, topological representations) that are largely missing from the framework in its current form. There are, in other words, commonalities in the representation of spaces across scales and across kinds (spaces, forms) that have been heretofore underappreciated. These commonalities are worthy of explanation. On the surface, they motivate an antecedent skepticism about the two-system view, in its current incarnation.

A modularist reply

These may all seem like trifling objections, but we happen to think they are serious. One could respond to all these observations by maintaining that the form and place systems have a modular and encapsulated architecture but with some ability to access the other's proprietary information. After all, in Section 1, we saw that Fodor was at pains to allow that modular (and non-modular) systems might share resources (as he took to be true of the modular systems involved in speech analysis). Alternatively, one could maintain the original distinction between form and place modules, doubling down on their use of distance and direction versus length and angle, respectively, while rejecting Spelke's conjecture that language is needed to integrate information across modules (2003; 2022; c.f., Duval 2025). Hence, one might maintain the original division of modular labor but maintain that our alleged counterexamples to this picture stem from the fact that, under certain conditions, the contents of the form and place system get combined, even in pre-linguistic creatures. The point to note is that: while we are sympathetic to this latter suggestion, in principle, the *entire reason* for positing two systems in the first place was the assumed fact that young children and other animals selectively use length/angle *or* distance/direction in different tasks, but not both. If there are inconsistencies in this starting assumption, it undermines the very reason we have for thinking that spatial cognition might comprise two distinct and informationally encapsulated modules.

A proponent of the two-system view might, instead, reply by reminding us that independent, neural evidence supports the view. After all, we saw in Section 2 that the proposed dissociation between a place module, that traffics in distance and direction contents, and a form module, that traffics in angle and length content, is supposedly reflected in the organization of the brain (Spelke 2022). The trouble is: Even bracketing well-known difficulties with making reverse inferences from neural data to conjectures at the algorithmic level (see Poldrack, 2006), let alone claims about informational encapsulation[5], the neural evidence itself is not as clean cut as proponents of the two-system view suggest. For instance, only *some* scene regions of the brain are sensitive to distance and direction (see Dilks et al., 2011; Persichetti & Dilks, 2016), while others respond to length and angle (cues supposedly reserved for the object system; Dillon et al., 2018). Likewise, object regions respond to direction contents even though direction content is meant to be encapsulated from the form system (Dilks et al., 2011). While these exceptions might be accommodated by the two-system view, especially in the absence of complete developmental data, the conjunction of considerable behavioral counterevidence, coupled with neural inconsistencies, forms a basis for doubting that the two-system view is accurate. This raises the question: What might an alternative framework for theorizing about the architecture of early geometric knowledge look like?

4 | The diverging algorithms hypothesis

While the two-system view enjoys prominence among advocates of the core knowledge theory, we are not the first to question its merits and motivations. Notably, Newcombe

[5] Neurophiles often miss this, perhaps because Fodor's (1983) devoted *an entire page* of his book to arguing that informationally encapsulated modules typically reduce to fixed neural machinery. We're not sure if Fodor's claim on this point was correct — although empirical critiques of this suggestion often miss the mark, denying such a reduction chiefly amongst the cognitive functions that Fodorians would readily deem *non*-modular (see e.g., Anderson 2016, p. 3). Regardless, in emphasizing informational encapsulation in his characterization of a module, Fodor's goal was to establish that a principled faculty psychology is *not* at the mercy of neuroscientific reduction and can be cast at an autonomous algorithmic/psychological level (see: Fodor 1974; 1997).

(2018) accepts certain tenets of the view — drawing on evolutionary, behavioral, and neuroscientific evidence, she accepts that there are two spatial systems, one for navigation and another for object manipulation (plus a third for symbolic spatial thinking). Nevertheless, she distances herself from Spelke and other adherents of the core knowledge hypothesis on the question of these systems' modularity: In particular, she denies that the systems under consideration are encapsulated from orthogonal geometric cues, on non-geometric contents, as Spelke and others submit. A virtue of the resulting story is that it allows for more flexibility; narrow exceptions to the patterns of information access posited by the two-systems view can now be accommodated by Newcombe's view. At the same time, it is unclear what positive predictions fall out of this view. The theory's flexibility threatens to render it less incisive.

To appreciate this, consider that — on all accounts — there is a robust pattern of developmental and comparative data that any adequate theory of spatial cognition must explicate. For instance, an adequate theory must explain why rats (Cheng, 1986), young children (Hermer & Spelke, 1994), and other creatures often neglect featural cues when reorienting and even seem to neglect to use certain geometric cues that are freely utilized in other spatial tasks (Lee et al., 2012). For reasons discussed, an appeal to encapsulation offers to explicate this. But while we side with Newcombe in holding that such full-blown encapsulation fails to withstand scrutiny, simply rejecting this encapsulation leaves us without an obvious explanation for these results. Simply put: Noting that the place module *can* access featural and/or angle and distance content fails to explain why this content is routinely neglected in the contexts which first motivated the postulation of a geometric and/or place module. Similar points hold for the form system: If the system is not encapsulated from sense information, we should still like to know why it often fails to make use of this.

How, then, might we proceed? One option would be to find ways of resurrecting the encapsulation of the place and/or form module, despite the concerns raised in Section 3. To this end, proponents of the two-system view might avail themselves of theoretical and empirical considerations that have been taken to insulate the encapsulation of other modular systems from purported counterevidence (Firestone & Scholl, 2016; Mandelbaum, 2018; Quilty-Dunn, 2020; Clarke, 2021). In flagging this, we wish to stress that we are not antithetical to claims about modularity and Fodorian encapsulation in general. On the contrary, we have often advocated for them (Clarke, 2021; Casser & Clarke, 2023; Clarke, *forthcoming*). Our position is simply one of skepticism over the idea that these defensive moves can save the encapsulation of the modules posited by the two-system view. The crux issue – as we see it – is not so much that a committed modularist might not find ways accommodate some or all of the counterevidence amassed in the previous section (although we are dubious); it is that doing so seems likely to tie them in knots and to leave the two-systems view without any clear motivation (see, for instance, our discussion of Shusterman and Spelke's [2005] proposal that the limitations of a place system can be bypassed by children's use of simple associative mechanisms).

A second option would be to abandon the dissociation between the place and form systems altogether. There are several pieces of evidence that, on their surface, appear inconsistent with a clear dissociation between these systems (and, for that matter, not so much evidence to support their strict dissociation in the first place). This option is therefore tempting. Strong claims about dissociability require strong evidence to be taken seriously, and such evidence is lacking in the case at hand — especially in comparison to other cases of modular processing which seem to us to be incontrovertible (see, e.g., discussion about the light-from-above assumption in the following section).

There is, however, another path forward. Rather than abandoning the dissociation altogether, we might posit a different *kind* of modular division between the form and place systems. This is conceivable because Fodor's characterization, framed in terms of informational encapsulation, is not the only way one can make sense of a system's modularity or algorithmic-level dissociability (Carruthers, 2006; Chomsky, 2017).

Our preferred alternative in this context turns on the fact that psychological systems might be individuated either by the *content* that the mechanisms have access to, *or* by the *computations* (the algorithms or procedures) they perform (Samuels, 1998). Thus, it may be that the place and the form modules are distinct on account of performing separate computations, individuated by distinct algorithms, but with access to the same *body* of information. In other words, these systems are individuated not by their content but by the algorithms performed over that content (see Figure 2).

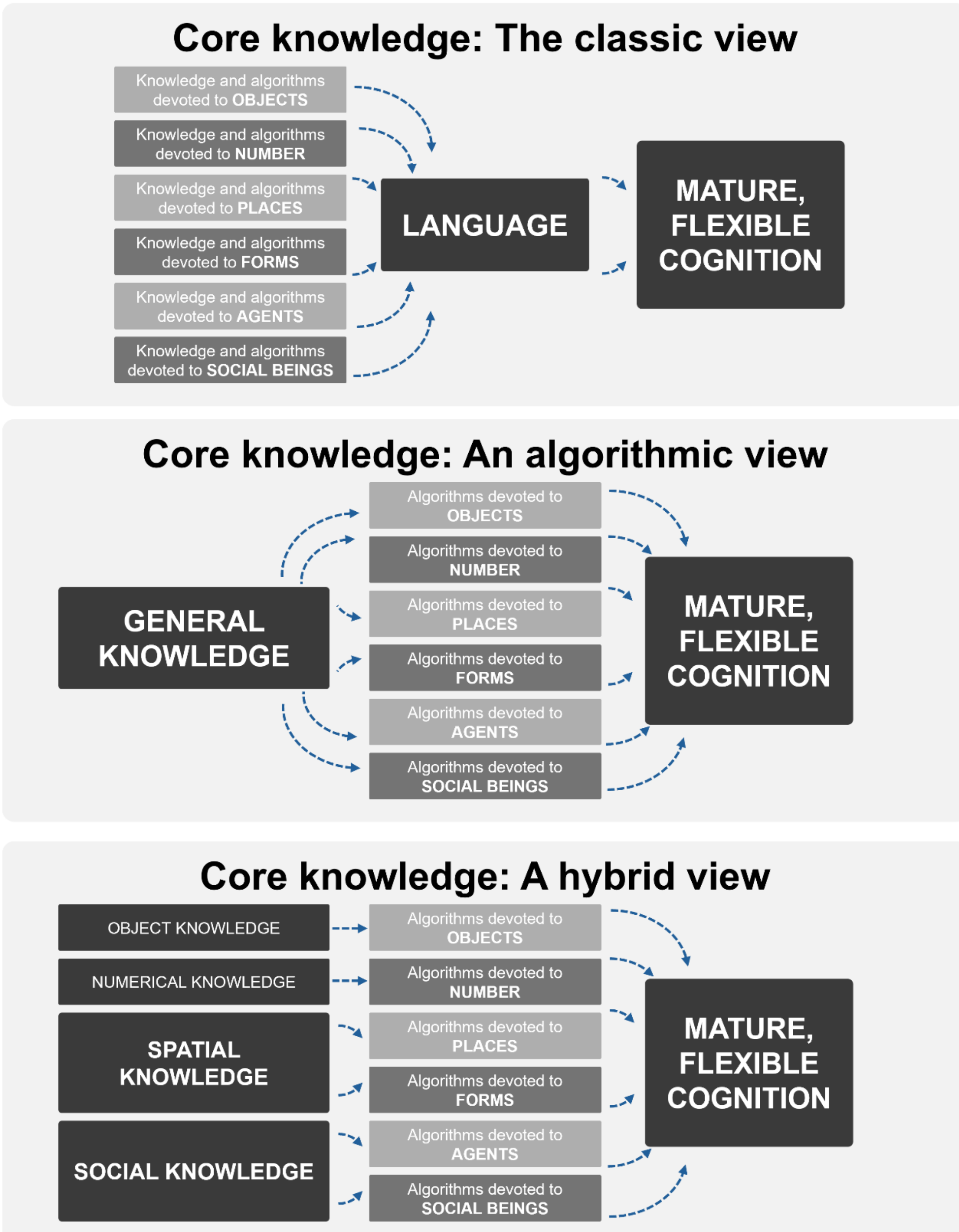

Figure 2. Different ways of thinking about the architecture of 'core knowledge'. The first view emphasizes distinct knowledge possessed by each module. The second emphasizes distinct algorithms. The third view is a combination of the two. We are not wedded to any one of these views.

Such a view is attractive since it offers to explain the patterns of developmental and comparative data under consideration. On the one hand, positing distinct and autonomous algorithms for navigation and form analysis offers to explain why the systems at issue exhibit different signature limits. The place system's algorithms may therefore dictate preferential usage of distance and direction information, at least under normal conditions, while the form system computations may dictate preferential use of length and angle. This is akin to the way that two search engines, employing different algorithms, might differentially weigh various pieces of information when given the same prompt such that they then produce results that diverge to a greater or lesser extent. On the other hand, and because our view allows that, the systems perform different computations over the same primitive representations, it allows that overlapping contents can sometimes enter into either system's operations — e.g., that sometimes the place system might use length, and sometimes the form system might use direction.

Crucially, on this view, the form and place systems are no longer conceived of as encapsulated from the features or geometric information that gets accessed by the other, enabling it to accommodate occasional counterexamples to Spelke's stricter Fodorian hypothesis. For instance, it allows that featural content might get made use of by the place system when the features in question are made particularly large and salient (c.f., Shusterman & Spelke, 2005), that these features might occasionally guide flexible navigational inferences (e.g., enabling target locations to be encoded as those which are one left of the blue corner — Newcombe and colleagues 2009), or that they might sometimes be considered in tandem with geometric contents that are more readily made use of in visual form analysis (Yousif and Lourenco, 2017). This is because the dissociation of the systems does not turn on the dissociability of the information that either system has computational access to.

At the same time: Our proposal still provides a framework within which to explain what an unqualified rejection of Fodorian encapsulation does not. For beyond accommodating counterexamples to the strict encapsulation of these systems, it provides a framework within which to understand why children and other animals continue to selectively prioritize certain geometric content and neglect to consider others when (e.g.,) navigating and reorienting in small to middle-sized environments or why orthogonal cues are prioritized and neglected in form analysis. In much the same way that proponents of core knowledge conceive of the modules they posit as evolutionarily ancient adaptations that are common across species (Carey 2009; Spelke 2022; c.f., Nieder 2021), our proposal allows that the form and place system (now demarcated by their diverging algorithms) might be products of ancient and/or convergent evolution that serves to cement the algorithms either system employs. As a result, it offers a framework within which to understand why children and other creatures typically make use of certain geometric cues to navigate, in apparent abstraction from featural contents that strike us (adult humans) as transparently relevant to the task being performed, while not requiring that these cues are always neglected.

To be clear, this proposal is not intended as a complete account of spatial cognition. It is proposed as a framework within which some such account might be developed. A complete theory would still need to identify the specific algorithms which actually dictate when information is and isn't employed by the place and form systems, and the parameters under which orthogonal cues become sufficiently salient that they get utilized in the tasks under consideration. Furthermore, it would need to assess whether, and in what way(s), these algorithms are innate. Nevertheless, it bears reiterating that some form of fixed algorithmic procedure underpinning place and form offers to explain why cues that might otherwise seem salient or relevant to a young child (BRIGHT BLUE AND STRIPED WALLS!) *fail* to guide their reorientation or form analysis in classic studies.

To illustrate how the framework might be developed: We submit that the algorithms which individuate the form and place are almost certainly innate in a way that our tendency to neglect star sign content whilst hummus shopping is not. We say this because it is relatively uniform in early development across species, and hence appears to be organized "in advance of experience" (Marcus 2009, p. 147). For this reason, we were tempted to label our proposed framework *the innate algorithms hypothesis*. Nevertheless, we still consider it to be an open question whether these algorithms are or can proceed to be shaped and refashioned by learning. That they might be is suggested by the fact that children can come to integrate featural content into their spatial reasoning following protracted training (Twyman and colleagues 2007; Lourenco & Cabrera 2015) and that older humans freely integrate such information when reorienting (Hermer & Spelke 1994). What we wish to note is that this is no foregone conclusion: In principle, such diverging algorithms might be fixed, much like certain tacit knowledge of grammar is on Chomskian accounts, yet later supplemented by the emergence or development of further cognitive resources, like language (Spelke 2003) or working memory (e.g., Spencer, 2020), enabling a greater breadth of cues and contents to be considered simultaneously in spatial reasoning tasks. In any case, none of this turns on the respective systems' encapsulation from orthogonal cues and contents.

All of this is to say: What we are really advocating for is a new approach to the study of spatial knowledge, its origins, and its development. On our preferred framing, the "hard core" of this research program (Lakatos, 1970) pertains to a need for diverging algorithms that explain the uniformity in developmental and comparative studies of reorientation and form analysis, while simultaneously allowing that these algorithms might access diverse bodies of content and knowledge. It is a framework on which more precise theories of these systems can now be built.

5 | Ramifications for the core knowledge theory

Our discussion has focused on the origins of spatial knowledge. Contrary to the two-system view, as it has been formulated within the core knowledge literature, we have argued that the evidence for the encapsulation of form and place modules is weak (Section 3). Moreover, we have argued that the behavioral dissociations that motivate the view can be neatly accommodated by our alternative diverging algorithms hypothesis, according to which the form and place systems are distinct on account of the algorithms governing their input-output functions, rather than information/content they have access to/are encapsulated from (Section 4). Given this, we advocate for a reconceptualization of the two-system view and its corresponding account of spatial knowledge in development. But how does this refinement bear on the core knowledge hypothesis more generally? To close our discussion, we wish to ruminate on this latter issue, noting broader ramifications and challenges posed by our results.

To appreciate these, it bears emphasizing that core knowledge has been regarded as a distinctive psychological kind, sandwiched between perception and mature and linguistically mediated thought on account of its architecture and relative abstractness. For instance, Carey (2009) conceives of core systems as akin to perceptual mechanisms in their modularity and in the iconicity of their representations, but unlike perceptual systems in that they trade in abstract contents, once thought to be the preserve of central cognition (but see Bai et al., 2025). Interestingly, Spelke (1990) largely accepts this picture, but rejects Carey's suggestion that core knowledge is wholly iconic (see also Quilty-

Dunn, 2019; c.f. Clarke, 2022). At any rate, the modularity of the systems involved is widely regarded as a defining feature of the psychological kind these theorists posit. Modularity itself — not just the specific knowledge that is posited to exist within those modules — is conceived of as a key feature of core systems. For this reason, it is worth considering how our rejection of Fodorian modularity in this one case bears on the broader hypothesis.

One possibility is that it offers a refinement that is wholly consistent with the architectural unity of core knowledge as a psychological kind. On this view, it might be conceded that the form and place systems are not encapsulated in the manner of a Fodorian module but individuated by their innate and proprietary algorithms (in the manner sketched in Section 4). Nevertheless, it might be thought eminently plausible to suppose that this is also true of other core knowledge systems, such that all core knowledge systems should be individuated in this way. Perhaps then this path might lead to a refinement of the core knowledge hypothesis without threatening the unity of the psychological kind being picked out by its architectural profile.

Another possibility, however, is that the arguments here point to a more substantive reevaluation of core knowledge. Specifically, in rejecting the informational encapsulation of the form and place systems, we raise a question about whether the broader umbrella of core knowledge can truly prove architecturally homogenous.

Why say this? Consider that one of the strongest motivations for the encapsulation of perceptual systems is that — while these mechanisms are inferential — they appear systematically incapable of integrating information that the subject knows and believes, no matter how salient or relevant its content. For instance, we noted in Section 1 that the visual system is widely seen to infer three-dimensional shape from patterns of shading, premised on the assumption that light comes from a single source *above*. This simplistic assumption serves us well in common environments that are lit by the sun or ceiling lights. However, it can also result in illusory percepts that systematically misrepresent reality. For instance, in the hollow mask illusion, a concave face is perceived as convex when it is lit from below, thereby inverting the typical correlations between shape and shading. What is crucial is that this illusion persists when known: Even when you reflect on your knowledge of the illusion, and/or attend to the lighting source below, your percept remains unchanged. So, while it is true that your visual system's priors about the source of lighting can eventually update, following long periods in atypically lit environments, this seems to happen via mechanisms that are not directly, or rationally, sensitive to your knowledge of the situation. But if this is correct and it is true to say that such knowledge *does not* rationally inform the perceptual inference (Pylyshyn, 2003), we should like to know why this is; and it is, here, that an appeal to Fodorian modularity seems well-placed. It is at least plausible to suppose that the reason why no one has ever managed to identify an example in which learning something new straightforwardly and synchronically alters visual perception in clear or compelling ways is that the systems involved in visual inference are encapsulated from our beliefs and knowledge about the situation (Firestone & Scholl, 2016).

We emphasize these points because some systems of core knowledge produce recalcitrant illusions of much the same sort. For instance, core object knowledge is seen to produce vivid illusions like the tunnel effect (Scholl & Flombaum, 2010); core knowledge of agency operates according to increasingly well-understood principles (Scholl & Gao, 2013), and in ways that are insensitive to reflection on the fact that the agents in studies probing these are simple squares and triangles (Heider & Simmel, 1944). Meanwhile, the approximate number system that is associated with core knowledge of number is subject to numerous illusions, like the connectedness illusion (Franconeri et al., 2009), the coherence effect (DeWind et al., 2020), and the crowd size illusion (Waterhouse & Yousif 2025) that lead to under/over estimations of numerical quantity. What is notable about each of these examples is not just that they result in illusions that are phenomenologically striking and readily appreciable, but that they *persist in spite of salient contradictory knowledge*. Recalcitrance indicates encapsulation; encapsulation indicates Fodorian modularity. While there may be some debate about the validity of these inferences (see, e.g., Prinz, 2006; Ogilvie & Carruthers, 2016), our point here can be stated modestly: In each of the above cases, core knowledge of objects, agency, and number still *appears* to be insensitive to certain known information and content, no matter how salient this becomes. Hence, something about the architecture or structure of the underlying systems must explain this. If we are right to deny that core knowledge of place and form exhibit similar recalcitrance from featural contents or orthogonal geometric cues, the architecture of these systems will still need to look quite different. This runs contrary to the proposed architectural unity of core knowledge systems.

It must be said that we are not the first to question the boundaries between different core knowledge modules. In the domain of agency, it has, for instance, been argued that agent representations are computed on the basis of principles of object individuation utilized by other modules (van Buren et al., 2017), whether in sensory perception (Bai et al., 2026) or core cognition (Carey, 2009; Spelke, 1990), perhaps because these systems form a hierarchy such that the outputs of core object knowledge serve as inputs to core agency discrimination (see Clarke, 2021). This, presumably, requires modular integration that obtains independently of language (*pace* Spelke, 2003; 2022). In a similar fashion, others have questioned the strict independence of modules for physical and social reasoning (Jara-Ettinger & Schachner, 2024; Liu et al., 2026).

What might seem more troubling for the broader theory of core knowledge is that some have argued for the wholesale rejection of other modular boundaries posited by the core knowledge theory. For instance, where proponents of the theory have typically argued for a dissociation between the discrimination of small sets, through parallel individuation (c.f., Barner 2017; Margolis 2021) and large numbers, as facilitated by an approximate number system (Feigenson et al. 2004; Spelke 2022), Cheyette and Piantadosi (2020) have recently argued that a single system, operating according to singular algorithm, yields the divergent behaviors that have typically motivated positing a modular dissociation between these systems. But without taking a stand on the question of whether Cheyette and Piantadosi's denial of these divisions is tenable (see Clarke *forthcoming* for concerns), it is important to note that, irrespective of whether there is one or two core modules for number, the remaining system or systems still produce recalcitrant illusions, like the connectedness illusion, noted above. As a result, the system or systems of core numeracy still appear to be encapsulated — or at least, architecturally distinct — from the systems of core spatial knowledge discussed here. Thus, core knowledge theorists still need to face up to the fact that there is less architectural unity amongst the systems being posited than these theorists would freely acknowledge.

6 | Conclusion

Our aim in this paper has been a targeted one — to scrutinize a specific modular division posited by the core knowledge theory (i.e., the division between a system for representing places and a system for representing forms) and to examine the consequences that follow from that scrutiny. We have argued that the evidence for informational encapsulation between the place and form systems is less secure than it might initially appear, riddled with — complicated, but underappreciated — counterexamples. As a way forward, we have sketched an alternative framework on which the form and place systems are distinguished not by their encapsulated proprietary databases (which may be part of one broader and/or shared cognitive 'library') but by the distinct algorithms that govern how spatial information is prioritized and processed in each context. Much remains to be worked out, including the precise nature of these algorithms, the conditions under which different cues are accessed by different systems, and whether any of this generalizes to other core knowledge domains. Yet this renewed skepticism promises to be productive. The proposed view, in a way, frees core knowledge theory from commitments to strict encapsulation that the data cannot sustain (and that for other domains may prove similarly cumbersome). At the same time, our discussion raises timely questions about the nature of core knowledge systems — namely, whether they are all architecturally homogeneous, or akin to perceptual processes in their modularity. If our hunches prove correct and these systems are not homogeneous, then core knowledge should be understood not as a unified psychological kind, but as a family of systems that share superficial features while differing in their fundamental architecture and in the nature and/or degree of their modularity.

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