THEORETICAL NOTE

Modularity in Cognition: Framing the Debate

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Modularity has been the subject of intense debate in the cognitive sciences for more than 2 decades. In some cases, misunderstandings have impeded conceptual progress. Here the authors identify arguments about modularity that either have been abandoned or were never held by proponents of modular views of the mind. The authors review arguments that purport to undermine modularity, with particular attention on cognitive architecture, development, genetics, and evolution. The authors propose that modularity, cleanly defined, provides a useful framework for directing research and resolving debates about individual cognitive systems and the nature of human evolved cognition. Modularity is a fundamental property of living things at every level of organization; it might prove indispensable for understanding the structure of the mind as well.

Keywords: modularity, cognition, evolution, development, genetics

A central question in psychology concerns the parts or processes of which the mind is composed. Prior to the cognitive revolution of the 1960s, it was popular to view the mind as a kind of black box and to view conjectures about its contents as unscientific. The cognitive revolution reversed this climate, rendering the search for the contents of the black box—a description of its internal structure that could account for the systematic relationships between information inputs and behavioral outputs—a key scientific objective of psychologists.

An important part of this enterprise has been the development of information-processing theories of mental phenomena, couched in the terms of the theory of computation. Central to computational approaches, in turn, has been *modularity*: the notion that mental phenomena arise from the operation of multiple distinct processes rather than a single undifferentiated one. Most psychologists today would probably agree that the mind has *some* internal structure: For example, the information-processing systems underlying perception are different in important respects from those underlying reasoning or motor control. However, beyond this modest agreement that the brain has *some* parts, there is little consensus on this important issue.

A Brief History of Modularity

The 1983 publication of Fodor's *The Modularity of Mind* (Fodor, 1983) launched a debate that has continued to the present day. In this book, Fodor proposed a particular account of mental structure in which information-processing modules of a very spe-

cific kind—reflex-like, hardwired devices that process narrow types of information in highly stereotyped ways—played a central role. The long-term effects of this book on cognitive approaches to the mind were twofold. First, because the vision of modularity it laid out was so narrow and well specified, it gave psychologists a potentially useful concrete concept to work with. However, for the same reason—the narrowness of the modularity concept—this work ultimately led virtually everyone, including Fodor, to believe that modularity as he defined it would eventually account for little of how the mind works (Fodor, 2000).

In the midst of this climate, other researchers, especially evolutionary psychologists, proposed that, contrary to the Fodorian view that only "peripheral" systems such as vision are modular, many or most information-processing systems in the mind might be modular as well. These included what Fodor would have called "central" processes, such as those underlying reasoning, judgment, and decision making (Cosmides & Tooby, 1994; Pinker, 1997; Sperber, 1994; Symons, 1987; Tooby & Cosmides, 1992). This proposal, sometimes known as the "massive modularity" thesis (Carruthers, 2005; Samuels, 1998; Sperber, 1994), has generated enormous controversy, including many attempts to demonstrate that massive modularity must be wrong, on either a priori or empirical grounds (Buller, 2005; Buller & Hardcastle, 2000; Deacon, 1998; Elman et al., 1996; Fodor, 2000; Panksepp & Panksepp, 2000, 2001; Quartz & Sejnowski, 2002; Ramachandran & Blakeslee, 1998).

This debate has, unfortunately, sometimes been more acrimonious than productive. Here we argue and provide evidence for the view that constructive progress has been undermined by the fact that opponents of modern views of modularity have critiqued modern positions as though the original (Fodorian) conception of modularity were intended. We also assert, as have other evolutionary psychologists (Barrett, 2005; Cosmides & Tooby, 1994; Pinker, 1997; Sperber, 1994; Tooby & Cosmides, 1992; Tooby, Cosmides, & Barrett, 2005), that a broader notion of modularity

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than the one Fodor advanced is possible: in particular, a modularity concept based on the notion of *functional specialization*, rather than Fodorian criteria such as automaticity and encapsulation.

Here we attempt to advance the modularity debate by clarifying what is and is not at stake, with an emphasis on preventing further debate and empirical work around issues on which there is not substantive disagreement. To do this, we divide the relevant literature into a number of critiques of the massive modularity thesis: cognitive architecture, development, genetics, evolution, and the computational theory of mind. The picture that emerges from this analysis is of a body of criticism that fails to engage the central reason that evolutionary psychologists and others have invoked the notion of modularity: functional specialization. We conclude with suggestions for how the differing perspectives in the massive modularity debate might be reconciled.

Fodorian Versus Functionalist Modularity

Fodor (1983) introduced his concept of modularity using a list of nine features he thought might be typical of modular systems. These included domain specificity, encapsulation, mandatory operation (automaticity), inaccessibility to consciousness, speed, shallow outputs, fixed neural localization, and characteristic breakdown patterns. Although these items have since been taken to be a sort of diagnostic checklist for modularity, Fodor himself was careful to emphasize that these were neither necessary nor defining features of modules (see also Coltheart, 1999). Instead, he suggested that "the notion of modularity ought to admit of degrees" and that when he referred to a system as modular, this meant that it was modular "to some interesting extent" (Fodor, 1983, p. 37). Fodor's (1983) treatment of modularity suggests that he took it to be a natural property with which certain features might be associated, but none strictly necessary (though he has since treated encapsulation as the most essential feature; Fodor, 2000; see below).

Should we treat modularity as something to be diagnosed via a checklist, as for Diagnostic and Statistical Manual of Mental Disorders (4th ed., text rev; *DSM–IV–TR*; American Psychiatric Association, 2000) Axis I disorders, or should we treat it as a natural property, which might not always reveal itself conveniently and cleanly? We agree with Sperber (1994), who suggested that, like other natural properties, the nature of modularity is something to be discovered. We similarly endorse the view espoused by many evolutionary psychologists that the concept of modularity should be grounded in the notion of *functional specialization* (Barrett, 2005; Pinker, 1997, 2005; Sperber, 1994, 2005; Tooby & Cosmides, 1992) rather than any specific Fodorian criterion. Biologists have long held that structure reflects function, but that function comes first. That is, determining what structure one expects to see without first considering its function is an approach inconsistent with modern biological theory.

The same holds true, we argue, for modularity: What it will look like in a given case—for example, whether or not it will entail automaticity or encapsulation—depends on the details of the mechanism in question. In short, we agree with Pinker (1997), who argued that modules should be defined by the specific operations they perform on the information they receive, rather than by a list of necessary and sufficient features (see also Sperber, 2005, p. 54). This stance allows us to look for specialization in cognitive pro-cesses that might not have much in common in how they process information (e.g., low-level perceptual processes vs. working memory) without prejudging the issue of what features might support specialized information processing in a given case.

If this argument is accepted, it has important implications for a number of arguments purportedly about modularity. In particular, an empirical investigation that reveals that a particular system lacks one of Fodor's (1983) properties of modularity does not license the inference that the system is not modular (examples of these claims are given below). This is the case even if one uses Fodor's own views, as he concedes that systems can be modular to a greater or lesser extent (Coltheart, 1999). Although a particular empirical investigation might indeed show that one or more of Fodor's features are implausible in a particular case, such a demonstration does not simultaneously demonstrate that a specialized system is implausible.

Of course, there will be a diversity of ways in which functionally specialized systems are instantiated, just as there is a diversity of ways in which the morphological features of organisms, specialized though they may be, carry out their functions. It is difficult to find a set of abstract features or a diagnostic checklist that captures under a single umbrella the functional properties of, for example, skin, hair follicles, the liver, the ulna, the eyes, the aorta, the islets of Langerhans, and the nucleus accumbens, even though each of these can be regarded as a modular structure from a biological perspective. In other words, the diversity of form–function relationships cannot be easily captured by a list of necessary and sufficient design features.

Modern Massive Modularity

Because there are extensive and exhaustive reviews elsewhere (Carruthers, 2005; Coltheart, 1999; Pinker, 1997; Samuels, 1998, 2000; Segal, 1996), we review here only briefly our view of modularity. Proponents of massive modularity have offered several reasons for expecting mental processes to consist of multiple specialized systems, rather than a single general purpose one. First, a large number of functionally specialized information-processing mechanisms are likely to perform more effectively and efficiently than a small number of systems with more general functions (Pinker, 1997; Tooby & Cosmides, 1992). For this reason, natural selection is likely to have favored developmental systems that give rise to function-specific cognitive mechanisms.

Along similar lines, information-processing systems face a variety of "computational tractability" problems, including what is sometimes known as the frame problem, or the problem of relevance, and combinatorial explosion (Dennett, 1984; Goodman, 1983; Quine, 1960; Samuels, 2005; Sperber, 2005). These problems derive from the fact that systems that must make inferences and decisions—such as the human cognitive system—face the problem that the possible inferences afforded by data are essentially boundless. This problem is probably best understood in perception, in which it has long been recognized that sense data have an infinite number of possible interpretations, and in linguistics, in which it has long been known that the linguistic information available to the child cannot by itself be used to induce the grammatical rules or the semantics of the language (Chomsky, 1965). These problems have in common that the computations required to reach the desired goal would require an enormous

amount of computational resources, time, or both. In some cases, no known computational procedure could reach the desired goal. For present purposes, the point is that mechanisms with narrow functions can embody information about the problem to be solved, thus avoiding combinatorial explosion. For this reason, natural selection is likely to favor specificity in the kinds of information handled by computational mechanisms.

Finally, because of the breadth of adaptive problems organisms face, multiple computational systems are required to solve these problems in a way that mirrors the multiple physiological systems in the body, most obviously visible in the form of organs such as the heart and liver (Tooby & Cosmides, 1992).[1]

Our position, then, is that functionally specialized mechanisms with formally definable informational inputs are characteristic of human (and nonhuman) cognition and that these features should be identified as the signal properties of "modularity." By this we intend an explicitly evolutionary reading of the concepts of function and specialization: modules evolved through a process of descent with modification, due to the effects that they had on organisms' fitness. Thus, natural selection, acting on the developmental systems that build modules during development, shapes the design features of modules. What matters, functionally, is *how modules process information* in the service of regulating behavior, because this is what impacts fitness. As a direct and inseparable result of this evolutionary process of specialization, modules will become *domain specific*: Because they handle information in specialized ways, they will have specific *input criteria.* Only information of certain types or formats will be processable by a specialized system. For example, systems specialized for assessing the numerosity of objects accept only representations previously parsed into distinct objects; systems specialized for speech perception process only transduced representations of sound waves; and systems specialized for making good food choices process only representations relevant to the nutritional value of different potential food items.

Thus, domain specificity is a necessary consequence of functional specialization. However, we wish to stress that we intend the broadest construal of the term *domain* to include, in principle, any possible means of individuating inputs. We do not intend a reading of domain as *content domain*, in the folk sense of domains individuated by the *meaning* of their constituents. Rather, we define domains as individuated by the formal properties of representations because, we believe, this is the only possible means by which brain systems could select inputs. As a corollary, by virtue of the fact that formal properties determine which inputs are processed, a mechanism specialized for processing information of a particular sort can, as a by-product, come to process information for which it was not originally designed, a point to which we return below.

Our view is that these aspects of information-processing systems exist not only in the peripheral systems but throughout the architecture. Ultimately, we will argue, the question of whether an information-processing system "is or is not" modular is not useful. There is little doubt that different kinds of information are handled by different systems in the brain. They can all be seen as modular in that they carry out specific tasks. The more important question, then, is this: What are the computational properties of the system in question? This question applies to all brain systems, from edge detectors in the visual system to a working memory buffer. When

this question is addressed, a yes–no answer to the question of modularity becomes unnecessary.

In our examination of the debate, we will use *massive* and *central modularity* interchangeably to refer to any proposals of modularity beyond the relatively uncontroversial thesis that some peripheral systems are modular. There exist various versions of the massive modularity claim, with some claiming that there is substantial modularity in central systems but allowing for some nonmodular processes, and others claiming that the mind is modular "all the way down" (Sperber, 1994; see also Tooby et al., 2005). Although we feel that the central–peripheral distinction will come to be seen as false or at least ill defined, proposals of modularity of central or "higher level" processes have generated the most controversy, so we focus on them here. Because there are strong intuitions as to what counts as a higher level process, we rely on these and conventions in the literature. In psychology, higher level or central processes typically include reasoning, inference, judgment and decision making, semantic processing, and so on.[2]

A classic example of a putative central or higher level process is reasoning. Cosmides's (1989) proposal of a cheater detection module to account for certain experimental findings generated substantial controversy (see below) and might be seen as an opening salvo in the massive modularity debate (Buller, 2005; Fodor, 2000), though language is perhaps the prototypical example of a putatively modular system (Chomsky, 1965; Fodor, 1983). In recent years, many additional modular systems have been proposed, including theory of mind (Baron-Cohen, 1995; Leslie, 1994; Scholl & Leslie, 1999); spatial orientation (Hermer & Spelke, 1996); number (Dehaene & Cohen, 1995); intuitive mechanics (Leslie, 1994; Spelke, Breinlinger, Macomber, & Jacobson, 1992); fear, disgust, jealousy, and other emotion systems (Buss, 1992; Öhman & Mineka, 2001; Rozin, Haidt, & McCauley, 2000); kin detection (Lieberman, Tooby, & Cosmides, 2003); and face recognition (Duchaine, Yovel, Butterworth, & Nakayama, 2004; Kanwisher, 2000).

As these proposals have proliferated, so have theoretical arguments against them. More often than not, these arguments do not confront the data but rather argue that modularity, in the instance in question, would be implausible or impossible on a priori grounds. When they do confront the data, they generally do so by showing that one of Fodor's modularity criteria is or seems to be falsified. We survey these kinds of arguments here. We note that in our attempt to impose a taxonomy on these arguments, they cannot always be cleanly cleaved, and elements of a particular argument often draw from others.

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[1] We disagree with Fodor's (2000) view that the function of human information-processing devices is to fix true belief; instead, information-processing devices evolved because of the effects they had on organisms' fitness in past environments, which may sometimes be related to true belief and sometimes not (Barrett, 2005). Pinker (2005) identified a number of difficulties with Fodor's argument, including the theoretical point that true belief does not necessarily always yield the best adaptive outcome and the empirical point that human minds seem to be poor at generating true belief in a number of domains (Kahneman, 2003).

[2] The terms *thinking* and even, oddly, *cognition* are often used to refer exclusively to central processes. We take both terms simply to refer to the information processing that the mind does, and we see no reason to restrict their referential scope.

Nevertheless, we feel that arguments surrounding either the implausibility of massive modularity or empirical claims of its absence derive from a set of fairly identifiable misunderstandings that fall under a small set of conceptual umbrellas. Our approach, therefore, is as follows. We review critiques surrounding four main areas: cognitive architecture, development, genetics, and spatial localization. For each, we review the corresponding argument with illustrative examples and explain how these critiques should be understood in the context of the view of modularity we advocate. We conclude with a discussion of a sketch of possible productive research agendas and the potential value that modularity adds to understanding cognition.

Architectural Arguments Against Modularity

A primary set of arguments surrounding modularity focuses on the issue of cognitive architecture. These criticisms draw heavily on empirical observations from human cognition and are rooted in claims that these observations are inconsistent with entailments of the modularity thesis. In particular, architectural critiques focus on the assumptions that modular systems must have access to only a narrow set of inputs and entail automaticity as a defining property of a module. Further, empirical observations of information integration across domains, flexibility in cognition, and the human ability to understand and respond to novel stimuli have all been suggested as inconsistent with the modular view. We address each of these criticisms below.

Is Narrow Information Access a Critical Feature of Modularity?

One major class of arguments about modularity revolves around the issue of what kinds of information the system in question handles or is designed to handle as inputs. Two Fodorian properties, domain specificity and encapsulation, can be considered in the context of this issue. Domain specificity (depending on whose definition one uses) refers to the idea that a given system accepts or is specialized to operate on only specific classes of information ("domains") for processing (e.g., Coltheart, 1999; Fodor, 1983; Samuels, 2005; Sperber, 2005). Encapsulation, on the other hand, refers to the idea that the information-processing procedures of a given system are not influenced by outside information or processes, other than their "proper" bottom-up inputs. (Encapsulation therefore rules out top-down and horizontal control; see Barrett, 2005; Fodor, 2000; Sperber, 2002.) These properties, however, can be difficult to tease apart. They depend on assumptions about modular structure: If one thinks about a module as a kind of pipe, domain specificity is a property of inputs at the entrance to the pipe, whereas encapsulation refers to the inability of external processes to influence processing inside the pipe.

If one relaxes the assumption that modules are like pipes (so that all potential influences on processing could be regarded as inputs), then the distinction between inputs to processing and outside influences on processing once it has begun disappears. In turn, the difference between domain specificity and encapsulation becomes ambiguous. Because of this ambiguity, Barrett (2005) suggested two alternative distinctions: *access* specificity/generality and *processing* specificity/generality. Some mechanisms might have *access* to large amounts of information in the mind but only *process*

information that meets its input criteria. Fodorian modules are widely assumed to have narrow access to information, but Barrett argued that many systems, including central ones, might have wide access but narrow processing criteria (e.g., systems generating inferences about the frequency of events might be sensitive only to information represented in frequency format, though information meeting this criterion could be present in many representational systems in the brain; Gigerenzer & Hoffrage, 1995).

It is clear that no computational mechanism can simply process any information in any way. Presumably no mechanism has access to all information in the mind. Moreover, even processing systems with relatively broad access, for example, the working memory system, have format requirements for the information they process. To simplify, if every cognitive mechanism has specifiable information that it accepts as inputs, even if some systems accept information in multiple formats (or can be controlled or influenced horizontally or top-down by other systems), then the crucial issue is the vocabulary of inputs a given mechanism accepts. No mechanism is either encapsulated or unencapsulated in an absolute sense. Cognitive mechanisms can be referred to as encapsulated with respect to certain information types but not others. What is important is to specify how information is accessed and how it is processed, including the input criteria that must be met for processing to occur.

This emphatically does not make modularity vacuous. For example, one can easily imagine "central" modules that have access to large swaths of central knowledge stores but process information in specialized ways (Barrett, 2005). (Internet search engines, for example, have these two properties: They are specialized but have access to the entire Internet; Pinker, 2005.) Modules, on this view, need not be restricted to the peripheries of the mind (Fodor, 1983, 2000). Instead, specialized systems can have a vast array of possible functions. The question of interest becomes the correct formal description of the set of inputs to a given information-processing device. Such a question affords empirical predictions: Inputs hypothesized to enter into a particular computation should influence that computation. Further, hypotheses about these inputs are derivable from a theory of evolved function (Tooby & Cosmides, 1992).

The focus on input conditions and function clarifies what is meant by "domains," because a theory of function will constrain hypothesized formal input conditions for information-processing devices. Sperber (1994) referred to the "proper" domain of a module as the class of inputs the module was designed by natural selection to process. For example, the proper domain of a face recognition system would be, putatively, faces of conspecifics (Kanwisher, 2000). The "actual domain" might be, and indeed in many cases must be, a broader class of tokens than the type for which certain modular systems evolved: for example, perhaps not only faces but the wider set of stimuli that have formal properties that cause them to be processed by the face recognition system. In addition, a view of evolved function informs hypotheses about inputs, including the contextual mediation of processing, as information about context can itself be an input to modular systems (see below).

Encapsulation, domain specificity, and other issues of information access are important in critiques of modularity because if one adopts the Fodorian view that modules, owing to the narrowness of their inputs and outputs, operate only at the early stages of infor-

mation processing (e.g., in perception), then it is difficult to see a role for modules at "higher" levels of processing, where information from diverse sources is integrated. Indeed, Fodor himself argued that the flexibility and globality of information processing at higher levels argue against a role for modularity (Fodor, 1983, 2000). This follows only from adherence to the narrow view of information restriction described above. However, we reject arguments suggesting that information integration is inconsistent with modularity. Such arguments do not undermine a *functional specificity* view of modularity but rather only challenge a Fodorian view based on narrow encapsulation. It is to this issue that we now turn.

Do Empirical Observations of Information Integration Undermine Modularity?

Claims surrounding information integration. Our view of modularity contrasts starkly with the Fodorian idea that modules cannot, in principle, integrate information from multiple sources because they are informationally isolated. Chiappe (2000), for example, suggested the following:

> To explain the human ability to integrate information from distant conceptual domains . . . we have to postulate unencapsulated cognitive mechanisms as Fodor (1983) suggested. We do not seem to be able to explain the full extent of our integrative abilities from a strictly modular perspective such as the one advocated by Sperber (1994) and other evolutionary psychologists. (p. 156)

Similarly, some endorse the view that empirical demonstrations of top-down or horizontal effects—cases in which higher level processing or processing by different systems influences the outcome of lower level processes—are inconsistent with modularity (Bishop, 1997; Farah, 1994; Hulme & Snowling, 1992). A classic example would be the McGurk effect, in which an experimenter can play one phoneme to a subject while simultaneously showing the subject the mouth movements associated with another phoneme. This leads to the subject reporting a phoneme different from the one that is played. Here, information from one modality, vision, influences auditory perception of phonemes (J. MacDonald & McGurk, 1978). In neuroscience, the activation of multiple brain areas when carrying out a particular task, suggesting integration of information from multiple sources, is sometimes taken as evidence against encapsulated modular processes (Bechtel, 2003; Farah, 1994).

There is also a class of arguments that "central" systems cannot be modular because they use information from multiple sources "flexibly," producing different outputs depending on context. Perhaps the most explicit argument is Fodor's (2000) claim that central processes are abductive and that neither encapsulated modules nor computational systems of any kind can perform abductive inference.[3] Processes like the pragmatic comprehension of speech acts, which involve global principles like relevance (Sperber & Wilson, 1995), would therefore appear to be cases for which modularity must be ruled out. Other cases in which content or context effects are observed in processing would also be ruled out on these grounds. Similar arguments would apply to staples of human cognition such as analogy, metaphor, and counterfactual reasoning.

Information integration does not undermine modularity. Although cases such as the McGurk effect, content effects on rea-

soning tasks, and the activation of multiple areas in functional magnetic resonance imaging (fMRI) might demonstrate the interaction of multiple systems and use of information from multiple sources, such findings do not falsify a hypothesis of principled and specialized use of information by dedicated systems. Empirically, what counts as evidence for or against a particular hypothesis about modularity turns on having a theory that predicts which inputs are relevant and, therefore, the psychological effects one expects to observe in different situations. Without such a theory, showing that information is processed differently in different situations or contexts, or that multiple systems appear to be involved or activated, tells us nothing about whether a specialized, or modular, information-processing system is involved. Context effects don't undermine the modularity thesis in general but might undermine a hypothesis that a particular process is encapsulated with respect to a particular class of inputs.

Consider visual illusions, which are regarded as among the most convincing demonstrations of modularity (Fodor, 1983). Not only are context effects (processing of the same stimulus differently in different situations) present in visual illusions, they are precisely what makes the demonstration convincing. In the most striking visual illusions, the exact same stimulus is processed one way in one context (e.g., the size of an object is accurately estimated with no background) but very differently in another context (e.g., when placed against a background with perspective cues that make the object appear larger or smaller, closer or farther away; Kaufman & Kaufman, 2000; Shepard, 1990).

Similarly, face inversion effects are used as evidence *for* modularity of face processing, not against it, even though they indicate that context, and not merely the structure of the stimulus itself, influences processing (Diamond & Carey, 1986; Kanwisher, Tong, & Nakayama, 1998). Sperber (2005) pointed out a similar context effect: A familiar face recognized quickly in one setting (a colleague passed in the hallway at work) might be recognized slowly, if at all, in another (the same colleague passed in an airport in a foreign country).

These examples are the same kind of evidence that Cosmides and others have used to invoke specialized processing by demonstrating that the same rule in the Wason selection task leads to different inferences depending on how the rule is framed in the preceding story text (Cosmides, 1989; Cosmides & Tooby, 1992; Fiddick, Cosmides, & Tooby, 2000; Gigerenzer & Hug, 1992). Briefly, in the Wason selection task, subjects are given a set of cards and a conditional rule of the form "if p then q" and asked which cards they must turn over in order to see if the rule is violated. For example, if the rule is "If a card has an 'X' on one side then it has a '5' on the other," then a card with an X showing must be turned over because anything other than a 5 on the reverse would constitute a violation of the rule.

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[3] Abductive inference (Fodor, 1983, 2000) can be glossed as "inference to the best explanation." For example, when scientists decide what is the best possible explanation for a set of observed phenomena, they are performing abductive inference. Abductive inference is said to be global, in the sense that any piece of information could, in principle, bear on the inference. See Pinker (2005) for a rebuttal of Fodor's claims about computation and abduction.

The key result for the present point is that the content and context matter in subjects' performance on this task. For example, simplifying somewhat, if the rule content is "If you have worked for 15 years then you receive a pension," whether the subject is put in the frame of mind of a worker or an employer will change, on average, which cards they report need to be turned over. Those in a worker frame "look for" employers who don't give deserved pensions, whereas those put in the frame of mind of an employer "look for" employees who get undeserved pensions (Gigerenzer & Hug, 1992). Data from a wide variety of experiments have been taken to show evidence of a specialized mechanism designed to detect cases in which a benefit has been taken while a cost has not been paid or a requirement has not been met (the formal definition of "cheating" in Cosmides's [1989] social contract theory).

The point is that evidence that processing is influenced by multiple systems or information does not rule out modularity; indeed, it counts as evidence in its favor when there is a principled theory surrounding the function of the mechanism that predicts the mediating effect of context.

These considerations are also relevant for experimental demonstrations that claim to undermine modularity by demonstrating cognitive penetrability of some putatively modular process. Experiments by Rozin, Haidt, and their colleagues (Rozin, Haidt, & McCauley, 1999; Rozin, Haidt, McCauley, Dunlop, & Ashmore, 1999) have shown that participants are reluctant to eat or drink substances that they know (i.e., have propositional knowledge) are harmless when these substances are in forms that evoke emotions such as fear or disgust. For example, Rozin, Millman, and Nemeroff (1986) showed that people who are offered fudge molded to resemble feces are reluctant to eat it as compared with a control condition in which the same fudge is in a different form. This is sensibly interpreted from a modular perspective: The fudge/feces has properties that admit the percept into systems designed to generate disgust, inhibiting the desire to eat it. The (propositional) information that the object is harmless—even tasty—does not seem to inhibit disgust, suggesting that the disgust-generation system is impenetrable to information in this format.

Fehr and Henrich (2003), owing in part to a misconstrual of cognitive penetrability as meaning "capable of understanding costs and benefits in novel situations" (p. 63), claimed that such experiments do not show cognitive impenetrability because subjects "would eat the fudge for a relatively small amount of money" (p. 63). The finding that people would eat fudge/feces for money has no bearing on the question of whether the percept satisfies the formal properties necessary to elicit disgust and, critically, on the question of whether propositional knowledge that the object in question is not, in fact, feces acts as an (inhibitory) input to the relevant decision-making system. If people will accept money to do things that elicit disgust, this does not mean that the computational system that generates disgust is penetrable to the fact that the fudge/feces is not feces at all. On the contrary, the fact that people must be paid to do things that they "know" (again, have represented in propositional form) are safe is testimony to the impenetrability of the computational system in question. If this propositional knowledge changed the output—disgust—then payment would not be necessary (indeed, many people *pay* to eat fudge).

In sum, the insistence on encapsulation, complete isolation from other systems, and insensitivity to contextual factors as criteria for modularity is misguided. Fodor (1983) initially invoked these

properties on the basis of considerations having to do with input systems early in processing, for which interactivity might be relatively unnecessary and indeed detrimental. For systems involved in inference, reasoning, judgment, and decision making, on the other hand—and indeed, for most systems other than very early perceptual processing—there is every reason to *expect* both interactivity and the integration of information from multiple sources. Not only are these features likely based on what we know about neural connectivity (Bechtel, 2003), they might be advantageous given the functional demands on central systems. These demands are likely to include information integration (e.g., reconciling contradictions in multiple information sources prior to action) and context sensitivity (e.g., making different decisions based on current hunger level, risk assessment, composition of current social group, etc.). Far from precluding the involvement of specialized systems, natural selection would favor the evolution of systems that adjusted their outputs in a principled fashion in response to changing features of the "global" cognitive environment.

Does Cognitive "Flexibility" Undermine Modularity?

Modular architectures have often been equated with "inflexibility" and contrasted with "plasticity," or similar terms. Ramachandran and Blakeslee (1998), for example, contrasted modularity with a brain that is "labile and dynamic" (p. 56). Panksepp and Panksepp (2000) argued against modularity, pointing to research that suggests "a vast plasticity in . . . cortical functions" (p. 116). Buller and Hardcastle (2000) put it succinctly: "Brain plasticity belies the idea of encapsulated modularity" (p. 311).

Although they share a common thread, arguments about flexibility come in a variety of flavors. Flexibility in information use, including information integration, which is one species of this argument, is addressed above. Arguments about flexibility in the context of development are a distinct species of argument, and are addressed in the section on development below. In this section, we address two specifically architectural claims about flexibility that are believed to pose challenges to a modular view of the mind: (a) that humans possess some domain-general mechanisms and (b) that human cognition is sufficiently versatile to deal with novel contexts, especially those that would never have and could never have been encountered in human ancestral environments.

Domain-general abilities. A number of domain-general skills have been proposed, including various forms of logical reasoning, working memory, and analogical reasoning (Anderson, 1993; Chiappe, 2000; Chiappe & MacDonald, 2005; Johnson-Laird & Byrne, 1991; K. B. MacDonald, 1991; Markman & Gentner, 2001; Newell, 1990; Rips, 1994; Stanovich & West, 2000). Fodor (2000) gave a precise version of the shape of arguments for domain-general mechanisms, which tend to turn on the idea that at least some mechanisms must be more domain general than others. In his discussion of a system that distinguishes triangles and squares (see pp. 71–78), he claimed that such a system must include some mechanism that takes as inputs both types of shapes and, from this, concluded that such a system is insufficiently modular to justify the massive modularity thesis—after all, at least some mechanism is "domain general," accepting as input both triangles and squares. This argument purports to show that if some distinction is made by the architecture, some mechanism must exist that is less domain specific than others in that it accepts a broader range of inputs.

Barrett (2005) has given one account of why this argument does not undermine the massive modularity thesis. He points out that this argument depends on assumptions about how information is routed to specialized devices in the brain. If, as Fodor assumes, information travels along prespecified, hardwired "pipelines" to reach the appropriate device, then it is true that there must exist a device that sorts the information prior to routing. This leads to Fodor's regress problem: For any set of domain-specific devices, there must be at least some devices broad enough to span their input domains.

Barrett, however, points out that not all specialized processing systems route information in this way, along prespecified channels. He points to enzymatic systems in biochemistry as an example and suggests an analogy between cognitive modules and enzymes. Enzymes with diverse functions and diverse processing criteria can have access to a single common pool of substrates, or "inputs," and yet still achieve specialized processing. Each enzyme has a recognition site that is capable of selecting its own inputs, or substrates, via a kind of "lock and key" template matching system. This means that each device is sensitive only to its proper inputs and therefore can select its own inputs from a common pool. No "metamodule," or routing system, is necessary in principle (for a related model, see Holland, Holyoak, Nisbett, & Thagard, 1986). In general, any case of a device that is sensitive to only one kind of input does not need a "meta" device to direct to it only those kinds of inputs to which it is sensitive. For example, eyes and ears are exposed to both light and sound, but eyes process only light, and ears process only sound. No routing device is necessary.

Widespread discussion of domain-general abilities still raises the question of how a domain should be construed (see above). Here we have suggested that domains should be construed in terms of the formal properties of information that render it processable by some computational procedure. In this sense, even the rules of so-called content-independent logics—for example, modus ponens—are domain specific, in that modus ponens operates only on propositional representations of a particular form.

For this reason, we disagree with Fodor (2000) and Sperber (2005), who appear to agree that modus ponens would count as a domain-general rule if it could operate on any propositional representations, regardless of their content. We argue, on the contrary, that modus ponens has a restricted and clearly defined input domain: representations in the form of if–then statements (see also Barrett, 2005).

There are strong intuitions about what counts as a "domain," many of which are not consistent with formal definitions by theorists such as Fodor (1983) and Marr (1982). To Marr, for example, the "domain" of a particular device could be as broad as *all object representations*, yet the device could still be a specialized, modular, computational device. Intuitions prevent some psychologists from accepting the idea that a module that processed all object representations is reasonably called domain specific, possibly because domain specificity implies to many differential processing of stimuli based on their "meaning," rather than their "formal properties" (Barrett, 2005; Fodor, 2000). The notion of meaning or content, however, is a folk notion: Human computational systems always process information based on formal properties—neural structures do not "know the meaning" of the information they are processing (Turing, 1950).

An example of this can be seen in a recent discussion of the development of face recognition systems. Morton and Johnson (1991) proposed the existence of a system that uses a kind of schematic template to pick out faces to facilitate learning. Buller (2005) suggested that the face template is domain general despite the fact that it appears to direct attention preferentially to face-like stimuli, which, in natural environments, tend overwhelmingly to be faces. Buller considers this system domain general because it does not have "full-blown innate knowledge" of faces (Buller, 2005, p. 154). This explanation misunderstands domain specificity. What makes a system domain specific is not that it has "full-blown innate knowledge" of its domain—a requirement that rules out all brain systems entirely—but rather that its procedures are *specialized* for the problem domain, even if this specialization is in some way heuristic. The face template, even if abstract and schematic, meets this criterion and almost certainly develops in the infant's brain in order to pick out faces. That the mechanism in question uses only a subset of available information speaks to the design of the system but does not make the system domain general; it does, however, give clues about the function of the system in question.

In short, modules' proper domains will all have inputs that are, in principle, able to be specified formally. Even modules whose proper domain is quite narrow—for example, an edge detector in early visual processing—will be activated on the basis of particular properties of the information they receive. The same will be true of, for example, a face-specific mechanism. It needn't "understand" that it is processing faces; it need only have procedures that are functionally tailored to solve the task. If the information required to do this is minimal, for example, low-level aspects of the configuration of objects, this doesn't make it any less face specific in terms of what it evolved to do, or in terms of what information it actually processes (Duchaine et al., 2004; Kanwisher, 2000). Unlike intuitive ideas about domain specificity, functional specificity affords a means of individuating functional domains using evolutionary functionalist principles to do so (in this case, for example, the importance of faces as a domain is suggested by the fitness benefits of being able to recognize individual conspecifics; Cosmides & Tooby, 1994; Tooby & Cosmides, 1992).

These considerations suggest that there is no natural line that separates domain-specific from domain-general mechanisms. It might be true that there are domain-general mechanisms in the sense that the inputs some mechanisms take do not neatly fit intuitions of what constitutes a domain (e.g., the domain of all objects), but it is nevertheless false that these mechanisms have no formal input criteria. Working memory has been proposed as an example of a domain-general mechanism (Chiappe & MacDonald, 2005), and it appears to fit intuitions about domain generality because working memory can process information about faces, cars, quantum mechanics, and so on. It is not "content limited" in the folk sense. However, modern accounts of working memory postulate functional specialized subsystems with very particular representational formats (the "visuospatial sketchpad," the "phonological loop," and the "episodic buffer") that together constitute working memory (Baddeley, 2002), whose function is to integrate information. This seems consonant with the version of modularity we endorse here, even though many psychologists probably do not think of these modular elements of working memory as domain

specific. Without a notion of functional specificity, we are left only with intuitions to determine whether working memory and its subcomponents are "modular" or whether they should be regarded as unspecialized and continuous with other systems.

Novelty. Humans unquestionably face and solve challenges their ancestors never faced. Examples are limitless, as new technologies have confronted people with problems from piloting aircraft to updating software drivers. Some see the very fact that people accomplish these tasks as fatal to the view we endorse here. Chiappe and MacDonald (2005) put it unambiguously: "From the perspective of modularity, it is difficult to see how humans could solve novel problems" because "there is no characteristic input–output relation based on past recurrences that can solve them" (p. 6; see also Sterelny & Griffiths, 1999).

Novelty is seen as a problem for modularity on two fronts. One is the development of putatively novel modular systems for over-learned tasks like chess or driving (Karmiloff-Smith, 1992), discussed in the section on development, below. Second, there is the handling of novel information in general. The argument based on characteristic input–output relations implies that the characteristic inputs of a module must closely match only inputs that were present in ancestral environments. However, this ignores the distinction made by Sperber (1994) between *proper* and *actual* inputs to modular systems. The role of natural selection is to shape a module's input criteria so that it processes inputs from the proper domain in a reliable, systematic, and specialized fashion. This means that in environments similar to those in which the module evolved, its actual domain (inputs actually processed) will closely match its proper domain. However, this does not preclude the processing of novel stimuli. Stimuli that happen to meet the input criteria of the device, even if they were not present in ancestral environments, can nevertheless be processed. Tasks such as driving, chess, and reading, although novel in their details, may nevertheless recruit evolved systems because they activate their input criteria. For example, evolved collision-avoidance systems could be recruited in driving, strategic social cognition systems could be recruited in chess, and systems evolved for identifying objects such as tools or animals could be recruited to identify letters or words in reading.

There are two possible readings of this claim. One is that modules develop normally and are *then* recruited for the task in question. For example, an object identification system could develop without any particular developmental influence from the experience of reading, and then be triggered by exposure to letters, which satisfy its input criteria. Another possibility, however, is that these experiences themselves contribute to the development of modules during ontogenesis. We return to this possibility below, in our discussion of development.

The argument that processing of novel stimuli militates against modularity hinges, in part, on the mistake of confusing tokens for types. Even stimuli that are clearly of a *kind* the system was designed to process—for example, faces—are always evolutionarily novel in that the particular faces one actually sees were not present in the past. Every stimulus an organism confronts is novel on some dimensions, and the actual outputs of specialized, evolved systems are always novel as well: They are specific phenotypic tokens of more general, evolved types. To illustrate this, West-Eberhard (2003) pointed to the example of the bones of the mammalian skull, which are joined by convoluted sutures. These

bones are properly considered modular, yet they differ in every individual in the actual details of their development. The cranial sutures in every person look different, like fingerprints, because their development responds dynamically to local developmental conditions.

Similarly, even at the lowest levels of information processing in the brain—where the modularity of the underlying mechanisms seems generally uncontested—novel stimuli are regularly processed. Object-parsing systems—which, presumably, are uncontroversially evolved, specialized, and modular—have no problem representing forks, airplanes, and automobiles even though these are evolutionarily novel. This is because systems for handling information about objects are designed to handle particular types of information—for example, information about the three-dimensional properties of middle-sized, spatially bounded entities—for which many tokens, even novel ones, satisfy the relevant criteria. A similar argument can be made regarding concepts. Clearly, "trombone" did not exist in ancestral environments, but the type TOOL or, at least, ARTIFACT certainly did, and it seems likely that conceptual templates exist that can combine various elements as novel tokens of conceptual types (Boyer, 2001; Jackendoff, 2002; Tooby & Cosmides, 1995).

Some will argue that there are certain cases, such as chess or driving, for which there is no conceivable evolved system that could handle the relevant stimuli as tokens of a more general type. However, an additional factor that contributes to the handling of novel stimuli is the ability of modular systems to generate novel combinations of elements (driving, for example, probably involves novel combinations of previously existing types of perceptual and motor skill). This is a characteristic of many evolved systems. Consider, for example, the human immune system. Modern humans encounter, fight, and overcome pathogens our ancestors never encountered. This is possible because of the "adaptive immune" system, which has a modular architecture: In particular, structures on the surface of lymphocytes have exquisitely specific binding sites that "recognize" an antigen exactly because it takes only that particular epitope (antigen) as an input—lymphocytes are domain specific in that each has specific input criteria. These recognition structures, surface immunoglobulins, give the system its flexibility because of the many combinations—tokens—they come in. Indeed, the system is *generative* by design, just as other modular systems, such as the language system proposed by Chomsky (1965), may be (Jerne, 1985; Piattelli-Palmarini, 1989). In each case, novelty (novel antigens, novel sentence tokens) is part of the adaptive problem each system evolved to solve.

Novelty is a potential problem for any architecture that is the product of evolution by natural selection. Every new organism faces a world that is different from the one faced by its ancestors, at least in the tokens if not the types of entities in the world. Evolution cannot prepare the organism for what is to be, only what was. Modular architectures provide flexibility because they allow components to be assembled and combined in novel ways.

In this context, it is worth mentioning that humans do not, in fact, always handle novelty all that well, and they operate, in many aspects of modern life, in ways that appear detrimental to fitness or to their own long-term goals (e.g., Burnham & Phelan, 2000). For example, people's propositional knowledge about the nutritional value of certain foods does not seem to guide behavior in a way

that optimizes health, possibly the result of the influence that proximate cues surrounding food have as inputs to the decision-making system associated with consumption.

Is Automaticity a Defining Property of Modules?

Fodor (1983) suggested that modular input systems were "mandatory," operating "willy nilly, in disregard of one's immediate concerns" (p. 55). That is, the presence of the proper inputs (e.g., a spoken sentence in a listener's native tongue) is a sufficient condition for the operation of the system in question, and when it encounters them, it processes them; one's "concerns"—conscious goals or attention, or indeed the operation of any system other than the one in question—are irrelevant. This property is sometimes called *automaticity* (Sperber, 2005)

A recent example of the construal of this property as central to modularity despite modern theorists' denial is DeSteno, Bartlett, Braverman, and Salovey (2002). They claimed that "evolved modules, by their very definition, constitute automatic mental processes that are activated reflexively (i.e., preconsciously) in response to specific triggering stimuli" (p. 1111). DeSteno et al. take the automatic/preconscious activation of modules to be definitional, citing Fodor (1983) (who preferred the term *mandatory*, though he did not regard it as definitional) but also, mysteriously, Pinker (1997) and Cosmides and Tooby (1994), neither of whom expressed such a view. Indeed, the terms *automatic*, *reflexive*, and *preconscious* do not even appear in the latter.[4]

On the basis of this construal of modularity, DeSteno et al. (2002) argued that if jealousy judgments are generated by a modular system that is automatic, then its operation should not be interfered with by placing subjects under cognitive load (having subjects keep in mind a long string of digits). Because they indeed found that cognitive load affected judgments about how jealous subjects would feel in various scenarios, DeSteno et al. inferred that these judgments were not automatic, undermining the notion of a "jealousy reasoning module" (p. 1113) suggesting that sex differences in jealousy are not due to evolution.

DeSteno et al.'s (2002) reasoning is multiply flawed. First, they claim that their findings "offer the strongest evidence yet that the ESD [evolution-predicted sex difference in jealousy] results not from evolved psychological mechanisms, but from an effortful decision process" (DeSteno et al., 2002, p. 1113). This apposition is a category error: All psychological mechanisms, whether they include "effortful" or "automatic" processing, are the product of evolution. Natural selection generated the cognitive mechanisms involved in effortful processing no less than any other mechanisms.

Further, automaticity (or "reflexivity" or "preconscious activation") need not be a definitional property of modules, and in fact it is not a criterion used by the authors of the works cited. Indeed, Kurzban, Tooby, and Cosmides (2001) took the reverse position, arguing that, in contrast to consistently expressed views (Fiske & Neuberg, 1990; Hewstone, Hantzi, & Johnston, 1991; Messick & Mackie, 1989; Stangor, Lynch, Duan, & Glass, 1992; Wegner & Bargh, 1998), the operation of the evolved, domain-specific system they investigated was *not* automatic with respect to categorization by race. Kurzban et al. (2001) suggested that because race was evolutionarily novel, it was unlikely that there would be evolved specialized machinery to categorize people along this

dimension (see also Cosmides, Tooby, & Kurzban, 2003). Their experiments showed that under certain conditions, categorization by race was attenuated, an effect that would not be predicted if such categorization were automatic. They inferred that the mechanism in question, although it might be designed to categorize people into different cooperative coalitions, was not designed to categorize people by race.

DeSteno et al.'s (2002) finding that decisions about jealousy change when people are required to remember digits suggests that some mechanisms that influence jealousy judgments operate differently when participants are under memory manipulations. That these particular systems are influenced by cognitive load speaks to the issue of whether the memory task and jealousy judgments share some computations in common under normal conditions. That does not mean that the mechanisms responsible for the computations performed under normal conditions are not modular in the sense of being function and input specific (see Harris, 2003, pp. 106–107, for a similar confusion).

Other experiments manipulating participants' attention make this clear. In inattentional blindness experiments, participants told to count how frequently a ball is passed among individuals in a video fail to observe a person in a gorilla outfit walk into the shot, perform a chest-pounding behavior, and exit (Simons & Chabris, 1999). On DeSteno et al.'s (2002) above arguments, the effect of this distracting task on the performance of the visual system leads to the conclusion that the visual system is neither modular (using Fodor's [1983] criteria) nor evolved (Sperber, 2005, used this example to make a similar point). Even Fodor (1983, 2000) endorses the view that input systems are modular, and to sustain their argument, DeSteno et al. would have to offer another causal process to explain the complex functional design in the visual system other than evolution by natural selection.

Whether automaticity or mandatory operation turn out to be useful concepts (Bargh, 1994; see Sperber, 2005, for a discussion of senses of "mandatory"), DeSteno et al.'s (2002) misconstrual of modern (i.e., Sperberian rather than Fodorian) discussions about modularity highlights the importance of conceptual clarity on the issue. Indeed, other than the trivial sense of "automatic," meaning that computations are carried out by virtue of underlying physical causality, "automaticity" in the sense of identical computations performed under any and all circumstances would be a puzzling design feature for organisms with many modular systems and many potentially different types of tasks to attend to at any given time. As Sperber (2005) pointed out, context sensitivity is both an

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[4] In Pinker (1997), "automatic" appears four times, and "reflexive" twice, but never supporting automaticity as a definitional property of evolved modules. Indeed, Pinker (1997) distinguishes his definition from Fodor's, suggesting that functional specialization, not features such as automaticity or encapsulation, is the central feature of modularity. Goldenberg et al. (2003) similarly mischaracterize Pinker's view and, in a discussion of DeSteno et al., further misattribute this view to Buss (1996) (who, like Pinker, emphasizes functional specialization; see p. 8), suggesting both authors assume that "innate modules constitute automatic, reflexive responses to specific triggering stimuli (e.g., Buss, 1996; Pinker, 1997)" (p. 1586). Goldenberg et al. (2003) misunderstand Pinker's (1997) position on modularity in precisely the same way as DeSteno et al., which is surprising because Pinker takes pains to distinguish functional specialization as the definitional feature of modules.

expected and an observed property of evolved systems. The inattentional blindness studies illustrate this idea for even low-level computational processes: Processing is modulated by context. DeSteno et al.'s claim that cognitive load should not impair the functioning of the systems in question suggests an architecture that is not only potentially extremely maladaptive in its inflexibility but also supremely inefficient, precluding the use of common computational resources by high-level systems. Moreover, mandatoriness in the Fodorian sense would lead to computational explosion, with all relevant systems generating outputs in the presence of every relevant stimulus (Sperber, 2005).

It seems uncontentious that some computational resources are shared by multiple systems and that the use of such a shared resource at a given time precludes its simultaneous use by another. Arguments about modularity do not turn on this feature of cognition, and although cognitive load manipulations might be informative regarding such shared resources, issues surrounding functional specificity and informational encapsulation require different experimental techniques (Barrett, Frederick, Haselton, & Kurzban, in press). More important, automaticity in the sense intended by DeSteno et al. (2002) is, like other features on Fodor's checklist, merely a possible feature that might apply to some modular systems but not a necessary feature of all of them.

Developmental Arguments Against Modularity

Critiques of modularity have not been limited to issues surrounding the nature of cognitive architecture, reviewed above. A number of criticisms have been leveled against the modularity thesis on the basis of arguments surrounding the relationship between modularity and development. In this section, we address these criticisms, with attention to the precise commitments the modularity thesis makes to the nature of the developmental processes that give rise to modular architectures. We similarly attempt to clarify the relationship between modularity and genes, an issue that has recently generated a substantial amount of debate. We begin with a discussion of innateness and nativism, both of which constitute focal points of contention.

Arguments About Innateness

In a recent review, Smith and Thelen (2003) identified what they believed to be two mutually incompatible views of how the complex, functionally specialized cognitive architecture in adults arises during development:

> Some . . . endow infants with genetically programmed and preexisting mental structures trapped in an immature body: latent capabilities for language, number, and physical and social reasoning that await revelation as infants mature. We . . . suggest that development is better understood as the emergent product of many decentralized and local interactions that occur in real time. That is, the developmental process is viewed as change within a dynamic system. (p. 343)

Smith and Thelen are not alone in contrasting a "nativist" view with an "emergentist" view (e.g., see Buller, 2005; Elman et al., 1996; Lickliter & Honeycutt, 2003). According to this dichotomy, there are two possible ways in which brain structure could arise. Either it is "innate" (also, "hardwired"), such that all aspects of the structure are specified in the genes (what might be called a

"strong" nativist view), or it "emerges" during development through the internal interaction of systems and processes in the brain and the external world. Typically, the strong nativist view is attributed to Fodor (1983, 2000), who along with Chomsky (1965) is regarded as an archetypal nativist (Cowie, 1998). This position has also been (mistakenly) attributed to evolutionary psychologists by researchers in this area (Buller, 2005; Buller & Hardcastle, 2000; Cummins & Cummins, 2003; Lickliter & Honeycutt, 2003; Panksepp & Panksepp, 2000, 2001; Quartz & Sejnowski, 2002). Establishing this dichotomy entails that *if* one rejects the notion of "genetically programmed and pre-existing mental structures trapped in an immature body" (Smith & Thelen, 2003, p. 343)—in other words, if one rejects the pre-19th-century doctrine of preformationism—*then* one must endorse emergentism.

Of course, no evolutionary approach to the mind (nor, more broadly, any contemporary scientific approach) entails preformationism (Tooby, Cosmides, & Barrett, 2003). By Smith and Thelen's (2003) logic, therefore, we must all be emergentists. We agree, because development must be the "product of many decentralized and local interactions that occur in real time" (Smith & Thelen, 2003, p. 343). This is simply a factual description, and there is nothing to deny.[5]

Emergentism should not be viewed as an alternative to an evolutionary approach. Both emergentism and evolutionary views make the same commitment to causal interactions between genes and the environment as the process that underlies the change from gametes to the mature organism. What separates the two approaches is not the fault line suggested by emergentists but rather the issue of *why* the emergent outcomes of developmental processes exhibit aspects of complex functional design that recur across organisms. We disagree with Smith and Thelen (2003), Elman et al. (1996), and other emergentists who imply that emergence is the ultimate cause of this organization per se, inasmuch as talk of natural selection, an obvious candidate for ultimate causation in the organization of biological systems, is avoided.

Pitting nativism against emergentism as competing explanations for development and organization of the brain (or any aspect of the phenotype)—in addition to creating straw men—commits a fallacy discussed decades ago (Tinbergen, 1968) but that curiously persists in discussions of evolutionary approaches (Kurzban, 2002). In particular, the error is the view that proximate and ultimate causal explanations are competitors, such that to the extent that one is true, the other is not. We strongly endorse what we believe to be the only biologically realistic position on the relationship between natural selection and development: that natural selection shapes developmental systems, including the dynamic, interactive processes that occur during the individual development of each organism, so as to produce developmental outcomes that are functionally organized in ways that have promoted survival and reproduction in the organism's natural developmental environment (for an identical position, see Tooby &

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[5] In fact, this statement describes every physical process in the universe (with the possible exception of nonlocal quantum processes). Therefore, in addition to being an emergentist about brain development, one must also be an emergentist about chemical reactions, geological processes, the formation of planets and solar systems, and everything else that can be explained as caused by physical processes.

Cosmides, 1992). It is difficult to improve on the phrasing of evolutionary biologist West-Eberhard (2003): "It is therefore misleading to engage in an either/or debate about whether selection or developmental mechanism (e.g. self-organization) explains an observed form. Both do, inevitably" (p. 65).

Does Modularity Entail Strong Nativism?

Given the foregoing, it is important to identify any commitments to development entailed by modular approaches that differ substantively from commitments that derive from other views of cognitive architecture.

In a way that parallels issues surrounding automaticity, evolutionary psychologists' views on nativism are often conflated with those of Fodor. Fodor is unambiguously a strong nativist. This is transparent in his strong nativist position on innate concepts (Cowie, 1998; Fodor, 1997). Regarding modules, Fodor is clear that modules are "presumed innate barring explicit notice to the contrary" (Fodor, 2000, p. 58). Yet he is also quite clear that his position is radically different from that of evolutionary psychologists such as Pinker (1997) and Tooby and Cosmides (1992). In addition to opposing claims of "central" modularity—an opposition driven by his views on encapsulation (see above)—he separates natural selection from modularity, doubting even that the functions of clearly modular aspects of the phenotype, such as the heart, should be defined in evolutionary terms (Fodor, 2000, pp. 86–87).

Specifically, Fodor (2000) takes the function of the heart to be its role in pumping blood in keeping him alive (pp. 86–87). More than just the semantics of the word *function* is at stake here, because functional hypotheses are supposed to do explanatory work. *Function*—couched in terms of a history of selection—is used by biologists to account causally for aspects of phenotypic design (Dawkins, 1986; Williams, 1966). The phenotypic design features of the heart—even Fodor's heart as an individual case—cannot be *explained* by Fodor's view of its function. They do not exist *because* if his heart were to stop pumping blood, he would die; their existence is due to causes that predate the current maintenance of blood pumping, stretching back beyond the birth of the individual. It is in this sense that evolutionary causes are relevant, however they might be instantiated by genes and environment during the developmental process.

Evolutionary psychologists have been quite clear and indeed insistent not just in their denial of strong nativism in the preformationist or "blueprint" sense implied by Smith and Thelen (2003) but also in their strong advocacy of an interactionist position that includes, as causal factors, genes, environment, interactions with the environment, and self-organizing processes during development (Cosmides & Tooby, 2000; Tooby & Cosmides, 1990; Tooby et al., 2003; see also Marcus, 2004). Moreover, the notion of "genetic prespecification" is not one defended by most evolutionary psychologists, but rather it is falsely included with their position by critics who continue to advance the strong nativism–emergentism dichotomy, a version of the nature–nurture dichotomy (Buller, 2005; Lickliter & Honeycutt, 2003; Quartz, 2002; Quartz & Sejnowski, 2002; Smith & Thelen, 2003).

This leaves the issue of the particular commitments about development that *are* entailed by a modularity hypothesis. If what individuates a module is functional specialization, as we argue

here, then a modularity hypothesis entails that the functionally specialized design features postulated by the hypothesis emerge in each individual, in each generation, during the developmental process by some process of genes interacting with internal and external environments. In other words, these design features are expected to *reliably develop* in each generation, even if the environment provides large amounts of the information relevant for the construction of the feature in question.

Reliable development, a thoroughly interactionist concept consistent with the tenets of developmental systems theory, has also been referred to as "design reincarnation" (Barrett, in press; Tooby et al., 2003) and differs importantly from genetic specification. For one, it suggests that if the normal environment of development is changed, developmental outcomes might be different. It also suggests that only certain elements of the final phenotype will reliably develop. Other parameters will vary, just as, for example, the size and shape and many features of hearts vary across individuals while certain functional aspects are invariant.

Reliable development, then, is a positive claim and implies that functionally specialized features of the phenotype will *emerge* during development given the presence of a normal environment (one that matches past environments along relevant dimensions; see Tooby & Cosmides, 1992). This view does not commit modularity theorists to the view that modules must develop in the same place in everyone's brain (see below) and that they must be identical in every respect. But if they develop properly, they *will* have certain functional features. In the cognitive case, they will exhibit specialization to process certain kinds of information in certain ways. There are many ways natural selection can engineer the gene–environment interaction to produce reliable development in normal environments.

Novelty in Development

Above, we suggested that the existence of evolutionarily novel skills, even potentially "modularized" skills such as driving, chess, or reading (Coltheart, 2002; Karmiloff-Smith, 1992), is consistent with the view that all modules have an evolutionary origin. On this view, novel skills, such as reading, might recruit evolved modular capacities, such as object recognition. The evolved object-recognition system presumably contains components dedicated to parsing objects on the basis of perceptual cues, categorizing them, and then linking them to systems for naming, semantics, and so on. All of these are also, plausibly, stages in reading (Coltheart, 2002). But could there be a module, or multiple modules, specifically dedicated to reading? And what would "specifically dedicated" mean in this context, given that reading is clearly a phenomenon of recent historical origin?

There are at least two possibilities for new skills piggybacking on older ones. One possibility is that a module or modules for object recognition develop more or less as they would have in a human who lived before the advent of reading. These modules would then be triggered or recruited by reading tasks, because reading satisfies the input conditions of the modules; they would be part of its actual, but not proper, domain in Sperber's (1994) sense. On this view, there would not be modules involved in reading that were *distinct* from those used in other object-recognition contexts. A prediction of this view would be that object and text recognition would dissociate together: They would

be retained or lost together in cases of impairment (we discuss dissociations in more detail below).

A second possibility, however, is that individuals who experience and practice reading develop modules that are different, phenotypically, than those that would have developed in the absence of reading. This is entirely plausible on the evolved developmental systems view we outlined above (and, we believe, more likely than the view that novel environments have no impact on development). But within this scenario, there are actually at least two possibilities for what the endpoints of development would look like. In one case, the experience of reading would influence the development of object-recognition modules such that the developed system, as observed in reading adults, would appear to contain specializations for reading. In fact, this is not such an implausible evolutionary scenario, even for specialized skills that are not novel, such as throwing projectile weapons; one might expect the motor and perceptual processes underlying throwing at the same time to be modular and to exhibit differences between novices and experts.

Under that scenario, one would again expect to find object and text recognition dissociating as a single unit, because the same underlying module or modules would be responsible for both skills despite having been modified during development to accommodate reading. Another view of modular development, however, allows for the *bifurcation* of modular skills during development: In essence, for phenotypically distinct modules to be spawned for specific, highly practiced or important skills (Barrett, in press). In this case novel tasks, such as identifying letters or words, would still be treated by the evolved developmental system as a special case (or token) of an evolved skill (object recognition) if they satisfied its input criteria. However, the developmental system in question could contain a procedure or mechanism that partitioned off certain tasks—shunting them into a dedicated developmental pathway—under certain conditions, for example, when the cue structure of repeated instances of the task clustered tightly together, and when it was encountered repeatedly, as when highly practiced (see Karmiloff-Smith, 1992, for a similar suggestion). Under this scenario, reading could still be recruiting an evolved system for object recognition, and yet phenotypically there could be *distinct modules* for reading and for other types of object recognition.

We regard this developmental scenario as highly plausible, if not likely. Indeed, the phenomenon of spawning new (token) modules for skills that fall under a particular type is something we might expect in a species, such as humans, whose evolutionary success depended on the acquisition of highly specialized skills (Cosmides & Tooby, 2000). If true, the *capacity* to develop novel phenotypic modules would be nothing new. Whereas now we have reading, chess, and driving, we once had tracking animals, warfare, and throwing projectile weapons.

Although we find it plausible, this scenario of module "spawning" is not a necessary entailment of the account of modularity we propose here. However, it does generate empirical predictions—in particular, predictions about dissociations—that are substantially different from those of the other scenarios we offered. Specifically, because under this account modules for novel skills would be phenotypically distinct, they would not, or need not, dissociate together. Thus, one could lose the ability to recognize text while other object-recognition skills remained intact. Another conse-

quence of this view is that different developmental trajectories of different skills are possible. For example, suppose chess grand masters do have a modularized chess skill, and suppose that this develops owing to a system designed to build modular social cognition skills, such as those involved in negotiation or other social strategic contexts such as warfare or politics. This need not imply that chess geniuses must also be social geniuses, because the actual modules responsible for chess skills and other social skills could be phenotypically distinct in grand masters. Indeed, if time spent on chess during childhood interferes with practicing of other social skills, one might often see poor social cognition in grand masters, opposite what one might expect if the same phenotypic module were used for both.

Do Modules Require Their Own Genes?

Some critiques of central modularity are concerned with the following kinds of questions: Are there enough genes to specify the number of modules required by the massive modularity hypothesis (e.g., Buller & Hardcastle, 2000)? Does each module need its own set of dedicated genes, and if so, how many? Has there been enough time since the common ancestor of chimps and humans for these genes to have been selected (Tomasello, 1999)?

There is pessimism about the answers to these questions, sufficient for Ehrlich (2000) to refer to a "gene shortage" (p. 124). Cummins, Cummins, and Poirier (2003) claimed that "genetic specification of an innate module will, as far as we know, require specifying synaptic connections in the cortex" but that "the human genome does not appear to have the resources to directly specify a significant amount of cortical connectivity" (p. 146). Similarly, Buller and Hardcastle (2000), in their argument "against promiscuous modularity" (p. 307), pointed out that even 40,000 genes could not code for the "literally trillions of synaptic connections in our head" (p. 314). Finally, Panksepp and Panksepp (2001) pointed out that because of humans' similarity to other species, instead of having more genes, our intelligence is best explained by humans' greater amount of brain tissue (Panksepp & Panksepp, 2000; see especially p. 120).

The pessimism of these views should be moderated by uncertainty surrounding some currently unanswered questions about modularity. First, how many modules are there? Second, what is the developmental pathway that links genes to modules in concert with the environment? Absent the answers to these questions, constraining hypotheses about modularity with reference to numbers of genes seems insurmountably problematic. Indeed, many aspects of the phenotype are sufficiently complex—including intracellular processes—that, absent detailed understanding of the relevant developmental process, inferring genetic requirements is essentially impossible. The complexity of the adult human cognitive system (and the rest of the human phenotype) is, by virtue of its existence, consistent with whatever number of genes is contained in the genome. Further, the modular view does not entail a commitment to a simplistic genetic deterministic view and is no different from nonmodular views in assuming that gene–environment interactions are crucial and complex in shaping phenotypes (Tooby & Cosmides, 1990, 1992).

In considering the issue of a gene shortage, it is important to distinguish between *architectural modularity* and *developmental modularity*. As discussed in the evolutionary developmental biol-

ogy literature, an aspect of the phenotype is developmentally modular to the degree that natural selection can act on it independent of other aspects of the phenotype (e.g., Griffiths, in press; Riedl, 1978; Schlosser & Wagner, 2004; Wagner & Altenberg, 1996). Architectural modularity refers to the endpoints of development—the degree to which the phenotype is "chunked" into functional components (e.g., Sperber, 2002). A single developmentally modular process can give rise to multiple architectural modules. For example, the process that produces hair follicles is presumably at least somewhat developmentally modular, yet it produces many millions of individual architectural modules in the form of individual hair follicles.

Does this apply to cognition? Module-like representational structures for face recognition are probably constructed for each face one can reliably recognize even though there are obviously no separate genes for recognizing each one. Architecturally modular novel tokens no more undermine developmental modularity than do novel tokens in other domains. The human immune system generates novel responses to parasites all the time (see, e.g., West-Eberhard, 2003, p. 58), yet no one seems to question whether there are sufficient genes to explain this process. Further, as discussed above, "high-level" modular architectures, such as the cognitive structures underlying chess skill, are probably tokens of module-generating developmental processes designed for other functions. The inference that such systems "cannot be based on a Darwinian algorithm" (Sterelny & Griffiths, 1999, p. 330) is unlicensed. Critics of massive modularity must articulate why novel cognitive tokens are more problematic than novel tokens elsewhere in the phenotype.

Further, developmental processes that give rise to distinct phenotypic structures in the brain presumably share many procedures in common as well as many of their necessary genes (i.e., genes that contribute causally to the development of the structure). Many developmental processes exhibit a nested hierarchical structure: They share common beginning points, with bifurcation or decision points during the process as structures become differentiated from one another and are more precisely specified (Gilbert, Opitz, & Raff, 1996; Riedl, 1978; see especially chap. 4 of West-Eberhard, 2003). Large numbers of modules in the brain might begin from a common starting point, and share many of the processes that build them, the more so the earlier one looks in development. This is a common pattern for evolved developmental systems in general (West-Eberhard, 2003). Subsequently, regulatory processes cause structures to diverge in their development, mediated by inputs from the internal or external world. In fact, different environments might cause different structures to develop by design (because of a history of selection for that outcome) even if there is complete overlap in the genes responsible for the development of the two different structures.

So, many of the processes and genes involved in the construction of modular structures are likely to be highly conserved. As elsewhere in evolution and development, new, specialized types might result from changes in very small numbers of genes or regulatory processes. Indeed, there might be many cases of distinct architectural modules that result from a single developmentally modular process. For example, one could imagine a system that develops different, modular information stores for different kinds of object—artifacts versus living kinds, for example—via a bifurcation process that is controlled by a single developmental pro-

gram, not two. There are few general facts or laws about how many genetic changes or mutations are required to produce new types of architectural modules. In the limiting case, one or a few mutations may be enough (as, for example, in the evolution of new photoreceptor pigments; Ihara et al., 1999). What is essential to note—and frequently misunderstood—is that the vast majority of developmental processes and genes involved in newly evolved module types are likely to be conserved, with little or no modification, from previously existing ones.

Therefore, the answer to the question "Does each module need 'its own' set of dedicated genes?" is no: Finding genes responsible for building that module and only that module is unlikely. Consider the genes "for" (in the sense of Dawkins, 1976) arms and legs. The genes that play a causal role in building arms and in building legs (as well as many other structures) overlap heavily. The same logic applies to the construction of mental modules.

As another way of seeing this, if one tried to specify the number of phenotypic details in the human body that reliably recur during development because of a history of natural selection acting on historically contingent developmental systems, one would certainly find that the number is greater than 30,000, the approximate number of genes in the human genome.[6] That is, it would require more than 30,000 parameters to specify the human phenotype in blueprint or informational terms. If such a one-to-one mapping were required, there probably wouldn't be "enough genes" to build a single cell in the human body (for a similar argument, see Marcus, 2004).

Finally, some have read the massive modularity thesis as a proposal that human cognition is characterized by a modular design that differs substantially from that of other species, and that there has not been enough time since the divergence of the human and chimpanzee lineages for enough genetic differences to accumulate to account for this difference (Tomasello, 1999). On this view, the differences between humans and, for example, chimpanzees cannot be due to the existence of a substantial number of novel modules. However, there are several reasons to be cautious regarding this claim. First, it may be that humans do in fact share large numbers of homologous modules with other species, in either identical or only slightly modified form. Second, although much has been made of the degree to which chimpanzee and human genomes are similar, the relationship between gene sequence similarity and phenotypic similarity is clearly not linear. Moreover, there appear to be relatively large differences in patterns of gene *expression* in human and chimpanzee brains, which could lead to substantial differences in brain organization (Enard et al., 2002). Finally, even "novel" modular structures in humans are probably modified from preexisting ones, and very small genetic changes may result in large changes in phenotype, with much of the developmental process that gives rise to the generation of modules

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[6] Tooby (2001) pointed out that whereas some authors take genes to mean protein-encoding sequences, a sophisticated view of development construes a gene as any sequence of nucleotides such that its modification generates a different outcome of the developmental process. Such a definition implies a number of genes much, much larger than 30,000. We use this number merely to illustrate the point that whatever the number of genes is, it isn't sufficient by itself to specify the human phenotype, in the sense of *specify* intended by proponents of gene shortage arguments.

remaining the same (Marcus, 2004). Thus, it is impossible to rule out hypotheses about novel modular structures in humans based on arguments about evolutionary time or genome differences.

Further Arguments Against Modularity: Spatial Localization and Dissociations

Is Spatial Discreteness in the Brain a Necessary Feature of Modules?

So far, we have dealt with two major categories of argument against the existence of modules: architectural and developmental. Now we turn to a final set of issues having to do with localization and functional dissociation. Psychologists generally agree—as do we—that because cognitive architecture is instantiated in brain architecture, the two will be isomorphic at some level (Marr, 1982). However, at a larger, macroscopic level, there is no reason to assume that there must be spatial units or chunks of brain tissue that neatly correspond to information-processing units. An analogy might be to the wiring in a stereo, a computer, or other electronic system: Individual wires have specific functions, but at the level of the entire machine, wires with different functions might cross and overlap. For this reason, removing, say, a three-inch square chunk from the machine would not necessarily remove just one of the machine's functions and leave the rest intact. In brain terms, it could be, and probably is, that macroscopic regions of brain tissue include neurons from multiple information-processing systems with multiple functions.

Fodor (1983), however, assumed that functional discreteness at the information-processing level would be reflected in discreteness at the macroscopic level of brain structure. Modules, on this view, would be like snap-in parts in an automobile engine. This led him to predict that modules would exhibit "fixed neural architecture" and "characteristic breakdown patterns," for example, following brain injury (Fodor, 1983, pp. 98–100). If modules are spatially localized and discrete, one might expect an injury that could impair a single module and leave all other brain functions intact. Here, we argue that modularity in the sense of functionally specialized information processing can exist even in the absence of evidence of spatial localization from, for example, fMRI or lesion studies.

Are Spatial and Functional Modularity Synonymous?

Possibly because the word *module* evokes images of spatially discrete units, claims about modularity have sometimes been understood as claims of *spatial* modularity: that a given mechanism is located in a particular part of the brain. Indeed, this idea has been taken to be central to modularity. Panksepp and Panksepp (2001) made the extremely strong claim that without evidence about "neuroanatomical location," "claims of evolved cortical modularity must be deemed insubstantial" (p. 71).

This, however, conflates functional modularity with spatial modularity. Functional modularity, as discussed above and elaborated below, entails a commitment to the view that cognitive mechanisms have narrow functions with circumscribed inputs. This is distinct from the claim that each functional mechanism will necessarily be localized to a small area of the brain. A given computational mechanism might be spread out widely across the brain (Pinker, 1997). Individual neurons, for example, carry infor-

mation, but functional systems require strings of neurons (distributed circuits) throughout the brain, a fact known to neuroscientists for decades.

The distinction between the computational description of a mechanism and its physical instantiation has been made many times in many contexts (Marr, 1982). Computational mechanisms can be instantiated in many different ways, only some of which will result in computations being narrowly localized. For this reason, evidence about the spatial location of computations must be treated carefully.

Take, for example, the finding that two different stimuli (or tasks) evoke the same or a similar pattern of activation in an fMRI study. Such results could be taken to imply that the region in question has a general function, processing both types of inputs. This is possible, but it is of course also possible that two mechanisms are involved, but beyond the spatial resolution of the imaging technology. In contrast, if two different areas are activated by two different inputs, this is more persuasive evidence that the two are treated by distinct systems. Findings that different areas are activated thus potentially afford greater inferential power than findings that the same area is activated, which represents an asymmetry in the way that spatial evidence can be used to draw inferences about specificity of processing (Shallice, 1988).

Similarly, findings that computational procedures can locate themselves in neural tissue in which they are not typically found anatomically have also been taken to be evidence against modularity (Quartz & Sejnowski, 1997; Ramachandran & Blakeslee, 1998). This is observed in cases in which there is damage to one area of the brain and the functions typically found there develop in another, often neighboring, area (see, e.g., Quartz & Sejnowski, 2002, p. 40).

The view that such findings undermine modular views derives from the mistaken belief that modularity entails a commitment to precisely programmed development. Quartz and Sejnowski (2002) suggested that, *in contrast* to the evolutionary view, "One possibility is that the information out in the world helps build your brain" (p. 41), as if evolutionary views allow no room for environmental influence, a patently absurd claim (see section on nativism, above).

In general, the fact that functions can develop in locations other than the ones that develop under normal circumstances is interesting and says something about the nature of developmental processes. It does not, however, falsify the claim that the systems that do get built are function specific. Indeed, the example Quartz and Sejnowski (2002; see pp. 39–40) use to illustrate their claim is quite specific. They describe a case in which tissue that normally takes visual inputs (occipital cortex) develops in such a way in blind individuals that it takes tactile inputs for purposes of decoding language (Sadato et al., 1996). This type of spatial plasticity is quite consistent with the idea that there has been selection to achieve the construction of cognitive systems with a certain degree of flexibility as to their location. Such flexibility would be an advantage of a system designed to ensure that requisite cognitive systems develop reliably, even under varied circumstances.

One can imagine other examples in which modular subunits get built in unusual places. A variety of vivid demonstrations have been made with fruit flies, showing that the development of entire modular structures can be manipulated by a small number of regulatory genes. For example, a change in a single *Hox* master

gene can cause an antenna to grow where a leg would normally be (Struhl, 1981). Presumably, few would take this as evidence that antenna and leg structures are not modular—indeed, it seems to give evidence in favor of the interpretation that legs and antennae are developmental modules whose developmental pathways can be triggered and substituted with relative ease. The same comments apply to demonstrations that brain structures can be made to develop in novel areas (e.g., Sur & Leamey, 2001). The fact that they retain elements of their modular structure, even when they occur in new places, is evidence in favor of modularity, not against it. Indeed, if the functional elements of these systems in the novel location were not sufficiently similar to the functional elements in the normal location, they could not be recognized as the same structure.

In sum, it is crucial to distinguish spatial and functional modularity. The claims we make here relate only to functional modularity. We remain agnostic with regard to the way that functional specificity is implemented in the brain and look forward to the accumulating evidence from developmental neuroscience to inform the details of these processes.

Does the Rarity of Perfect Dissociations Argue Against Modularity?

One of Fodor's original criteria for modularity was "characteristic and specific breakdown patterns" (Fodor, 1983, p. 99). The rationale was that if a particular process is handled by a discrete, modular system, then damage to this system from a brain lesion or developmental disorder should affect this process while leaving others relatively intact. This criterion has sometimes been used to argue for modularity in specific cases, especially in the case of "double dissociations" (Teuber, 1955). Briefly, a double dissociation is said to occur when some causal event (e.g., damage to the brain, experimental manipulation, developmental disruption) affects some process, say A, but does not affect another, Process B, while another causal event affects Process B but not A. If two such causal events exist, it can be reasoned that Processes A and B are distinct. (See Dunn & Kirsner, 2003, and Coltheart & Davies, 2003.)

Critics have pointed out, however, that such patterns are almost never clean (Elman et al., 1996). A possible inference to draw from this observation is that almost nothing in the brain is truly modular. However, there are a variety of reasons, well explored in the neuropsychology literature, for which lesions to brain systems can produce noisy rather than clean patterns of breakdown even when the systems required to complete a given task are modular (Shallice, 1988).

Drawing inferences about brain architecture from dissociation patterns is not trivial and has been discussed at length elsewhere (see, e.g., Caramazza, 1986; Shallice, 1988). Briefly, if individuals' brains consist of relatively similar functional modules but are slightly different from one another, damage to any given brain will produce unique patterns of breakdown. That is, although there might be some regularities in which functions are spared or impaired given damage in a particular region, some variation is to be expected. The motherboard of a conventional desktop computer provides a good analogy. It is entirely modular in design, both spatially and functionally. However, hitting the motherboard with a hammer or drilling small holes in random locations would

probably not result in clean dissociation of individual functions, and it would be difficult to make inferences about the underlying architecture from the machine's altered performance.

In most cases, no two lesions will result in the same kind of damage, even if they are directed, for example, systematically to one part of the board. Moreover, there might be asymmetries, with performances on some tasks more impaired than others, rendering truly clean double dissociations rare (e.g., it might be possible to obtain a DOS prompt but not to start Word, but not because the DOS architecture is not modular). In brain systems, it has long been known that different processes might be differentially susceptible to damage, even if both are specialized (Shallice, 1988). Moreover, comparing patterns across subjects is difficult because lesions are almost never identical, and the location of specialized systems can vary across patients (Caramazza, 1986). Thus, noisy rather than clean breakdown patterns—patterns that are asymmetrical within individuals and that vary across individuals—are what one would expect, even from an entirely (functionally) modular system.

It is worth emphasizing again, as we mentioned above, that there is an asymmetry in our ability to make inferences from lesion data (for an extended discussion, see Shallice, 1988). When double dissociations *are* found, this is strong evidence for modularity, and moreover, it can be used to make inferences about the design features of the modular systems that dissociate. However, when double (or single) dissociations are not found, it is not possible to make the reverse inference, namely, that the systems involved are *not* modular. This asymmetry arises not from any theoretical bias "in favor of" modularity but because of the facts about how damage occurs: There are many ways to damage brain systems, not all of which will cleave modules neatly.

Discussion

Terminological disagreements have hampered efforts to disentangle important issues surrounding the term *modularity*. Since Fodor's (1983) book, not only have authors used the term *modular* to refer to different concepts, but even explicit definition of the term by some researchers has been insufficient to avoid subsequent misunderstandings by others. In particular, the equation of *modular* with "fixed," "innate," and "static" is an understandable consequence of intuitions that underpin the term, with its admittedly multiple metaphorical entailments; however, this has led to the propagation of confusion, some of which we hope to have ameliorated with our discussion here.

Ultimately, we hope that what is at stake is not terms but rather the concepts that correctly characterize the way that the mind/brain develops and the architecture that results from developmental processes. Our discussion has been embedded in a particular view of cognitive development and architecture. Our interactionist perspective, that all cognitive mechanisms are the result of a developmental process that involves genes and environment as both causally relevant, is relatively uncontroversial. It is probably too much to hope that the rabid insistence on interactionism by some authors will end as a result of the fact that there is no serious opposition to this view, but if the future is like the past, we expect that the construction and destruction of simplistic genetic determinism is likely to continue.

There are, to be sure, genuine points of controversy. Our endorsement of the view that some version of the computational theory of mind is going to turn out to be true might be a point of genuine disagreement (Fodor, 2005; Pinker, 2005). However, absent good alternatives, we feel reasonably well justified couching these issues in these terms. We believe that the view of modularity suggested here is essentially logically entailed by a computationalist perspective, which is committed to mechanisms with formally definable inputs and operations. We hope that the present proposals about modularity will be relatively uncontroversial for those who endorse computational theory of mind, although we have no doubt that some will disagree.

Another potentially controversial aspect of our view is that the genes that play a causal role in the developmental programs associated with cognition have been selected by virtue of the functional outcomes associated with the ultimate products of the developmental systems. We believe that these programs are likely to have been selected by virtue of their history of bringing about functionally specific, architecturally modular structures associated with adaptive problems faced by our ancestors. In modern environments, these architectural modules are unique, and occasionally systems are generated with little parallel in human history. Developmental modularity leads to novel tokens of architectural modules. There do not seem to be any appealing scientifically viable alternatives to this explanation, but, as Fodor (2005) has pointed out—emphatically and in CAPITAL LETTERS (see p. 31)—this is subject to further discussion.

We hope we have not erected any straw men. However, the view from evolution and functional specificity can be easily contrasted with some approaches that make very different predictions. Consider, for example, game theoretical perspectives, which generally suggest that people should apply any and all knowledge relevant to strategic interaction, but no other. Recent work implies that behavior in various contexts is influenced by cues that might have been relevant in ancestral environments even though their use in modern contexts makes little sense from the standpoint of canonical models of economics, even those that incorporate preferences beyond self-interest.

For example, Haley and Fessler (2005) showed that people chose to allocate more money provided to them by an experimenter to an anonymous other in a condition in which stylized eyespots were present on the computer screen in front of them as compared with a control condition (see also Burnham & Hare, in press). This effect is comprehensible from the perspective of modules designed to be sensitive to cues of social presence but not other theoretical perspectives (see also Kurzban, 2001). In general, the canonical view in economics is coming to be replaced by much more sophisticated and nuanced understanding of actual human psychology (Camerer, 2003).

It is also important to note that the view endorsed here has no special role or ontological priority for beliefs. From a functionalist perspective, some modular systems might be penetrable to beliefs or other propositionally represented knowledge, and others might not be (e.g., see Barrett et al., in press, on propositionally represented knowledge influencing jealousy reactions). The issue of why beliefs enter into some computations but not others flows from the developmental programs involved in the construction of architectural modules that either are or are not influenced by beliefs. Clearly, many perceptual processes (Pylyshyn, 1999) and affective responses (Rozin et al., 1986) are not influenced by representations akin to beliefs, whereas other kinds of processes are. We mention this because the notion of "belief" has played a role in both terms and theory surrounding modularity. However, beliefs should be considered no differently from other sorts of representations.

What Value Does Modularity Add?

Fodor's (1983) list of features of modular systems gave cognitive scientists a conceptual vocabulary for talking about the degree to which a system could be considered modular. This constituted a conceptual advance, but it would be a mistake to suppose that the definitive word on modularity was given more than 20 years ago. In our discussion, we have abandoned several of Fodor's initial properties of modular systems, so much that one might wonder if there is enough left of the concept to be of value. We believe that there is: Post-Fodorian modularity is not vacuous.

First, recall Sperber's (1994) point that modularity, if it is a property of the human mind, is a matter of discovery. Second, it is worth emphasizing that we take the signal feature of modularity to be specialization of function. As a corollary, to carry out their specialized functions, modules can be predicted to operate on only certain kinds of inputs or to privilege inputs relevant to that function. These principles lead to some basic conclusions regarding the utility of the concept of modularity.

First, the modularity thesis informs empirical investigation by directing the search for specialization. Although we have discussed a number of issues that do not divide researchers in the cognitive sciences, we do believe that there is continued debate regarding the degree to which cognitive mechanisms are specialized. Modularity provides the conceptual tools with which to resolve these types of debates. Instead of checking off Fodorian properties of a candidate system, modularity can be investigated by testing claims about the degree to which a mechanism is specialized by careful empirical work on each candidate system. Cosmides's (1989) work on logical reasoning is a canonical example—subject to interpretive debate to be sure (Fiddick et al., 2000; Sperber, Cara, & Girotto, 1995)—but it is useful because this work has focused attention on the question of whether there are systems whose functions can be stated in very general terms (relevance, deontic reasoning) or a collection of systems whose function must be stated more narrowly (cheater detection, precautions). In particular, positing a functionally specialized cheater detection module forced Cosmides and her collaborators to be explicit in developing a computational theory, including inputs and outputs, rather than "black boxing" the system in unfalsifiable vagaries.

Further, evolutionarily informed research surrounding modularity adds an additional element, because it highly constrains the hypothesis space regarding plausible functions—they must be ones that would have contributed to human ancestors' reproductive success. This is a nontrivial limitation and immediately eliminates a vast array of hypotheses that entail functions outside this scope. It is worth noting that although there are principled reasons to expect that natural selection favors specific rather than general mechanisms, this principle applies equally to function-general and function-specific systems. Even systems with very general functions—however these functions are stated—must be ones that are plausible from the adaptationist framework.

Along similar lines, modularity directs empirical investigation by providing a priori hypotheses about which inputs will have an influence on a given module's operation. Again, if the evolutionary view is taken seriously, then any given functional domain should have predictable inputs relevant to that system's function. In this way, modularity in the sense of functional specificity potentially informs issues of input specificity, the formal properties of the representations that will be processed by a mechanism with a given candidate function, and the contexts in which processing will occur. The evolutionary view and the modular view dovetail with one another, yielding potentially large amounts of empirical fruit by forcing careful consideration of inputs that would have aided in directing adaptive behavior. Research on phobias, in particular their acquisition, has been productive in part for this reason. The fact that people readily acquire fears of entities very unlikely to do them harm in current environments (e.g., snakes) but develop no such fears with respect to more common potentially harmful objects (e.g., electrical outlets) is an example (Marks, 1987; Öhman & Mineka, 2001).

Similarly, specific hypotheses about architectural modularity inform not just the issue of the information that might be accepted as input in a given domain but also the formats that are likely to be processed. Functional specificity, by itself, is relatively silent on the issue of format, but a commitment to modularity forces consideration of precisely this issue. From a purely functional standpoint, there is a sense in which all informational content, independent of format, is created equal. As long as a given piece of information is relevant to the function, the functional view implies that it should be consumed by the mechanism in question.

However, even without an evolutionary view of the modularity thesis, functional specificity highlights the importance of careful thinking regarding inputs and suggests that all information is not created equal. The work of Gigerenzer and colleagues (Gigerenzer & Hoffrage, 1995) is illustrative. Gigerenzer and Hoffrage (1995) gave participants information needed to solve various problems either in the form of frequencies (e.g., 8 out of 10) or in the form of probabilities (e.g., .8). When information was presented in the form of frequencies, people solved the problems more accurately. From a strictly mathematical perspective, the information presented to participants is exactly equivalent in the two conditions. Information in both formats is sufficient to generate a correct response if participants used Bayes's theorem. However, what counts as the "same" information from the perspective of a normative mathematical theory such as Bayes's theorem might not count as the "same" information from the perspective of an evolved information-processing mechanism. In this case, it seems to be that mechanisms performing relevant computations take frequencies as inputs more readily than probabilities.

In addition, taking a modular view rationalizes debates surrounding how best to characterize a given mechanism's function. Sperber's (1994) distinction between proper and actual domains is valuable here, and it seems likely that debate in several areas might be aided by the use of these concepts. The face recognition system is a good example. Demonstrations that a given mechanism can be trained to operate on stimuli that are not faces can easily be accommodated by the notion that these stimuli are in the mechanism's actual rather than proper domain. This finesses the question of the issue of "how specific" the mechanism is by sensibly dividing up the question into two parts: What was the mechanism designed to do, and, in modern environments, what does it actually do? The answer to the first can inform empirical work on the second, and empirical results regarding the second can inform the first.

Finally, framing issues in terms of modularity may help to resolve the controversy over the commitment of evolution-minded researchers to a constellation of highly function-specific mechanisms. Determining how function specific given mechanisms are, along the lines of the research agendas sketched above, will contribute to this debate. To the extent that mechanisms do not show the sort of functional specificity to which evolutionary psychologists have committed, such evidence undermines the empirical basis for these claims. It might turn out that many aspects of the cognitive architecture of humans will consist in devices that are more general purpose than those proposed so far by evolutionary psychologists. Demonstrating modules with very general functions would play a potentially major role in deciding this question.

In sum, any given hypothesis about the design of a given cognitive mechanism might turn out to be incorrect. Some ways in which these hypotheses will turn out to be wrong seem less likely than others. It seems unlikely that a given mechanism will not have evolution as part of its causal history or that the mechanism in question developed with no interaction between genes and the relevant environment of those genes. However, the details of the functions that mechanisms carry out, in particular their specificity, are the subject of debate and empirical inquiry. The language of modularity affords useful conceptual groundwork in which productive debates surrounding cognitive systems can continue to be framed.

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