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Modules in the Flesh

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Is the mind modular? Any answer to this question must have at least two components: a definition and data. Because there is not yet widespread agreement about what we want "modularity" to mean, a satisfying answer to the modularity question is still out of reach. Most current debates about modularity are largely about semantics. People interested in facts are inclined not to get involved. Moreover, because of the narrow definition of modularity offered by Fodor (1983), most cognitive scientists, including Fodor himself, are inclined to believe that little in the mind is modular (Fodor, 2000). Modularity, according to this view, might be a useful concept for some little pieces of mental structure here and there, but not for *most* of psychology.

This view is mistaken. Most cognitive scientists associate modularity with specific features, such as isolation from other brain systems, wholecloth innateness, and automaticity. This leads them to overlook what should, in fact, be regarded as the central feature of the modularity: *functional specificity* (Barrett & Kurzban, 2006; Tooby & Cosmides, 1992). This is the part of the modularity concept that the psychological sciences cannot afford to throw out. Among other things, it is a critical foundation for the testability of psychological theories. At present, the language of modularity, broadly construed (as opposed to Fodor's [1983] specific feature list), is the best language we have for talking about the functional specialization of mental processes. We might ultimately choose to not use the term "module" to refer to specialized information-processing structures, but we cannot discard the concept itself.

Different people mean different things by "modularity." Evolutionary psychologists have been particularly vocal in stressing that the prevalent view of modularity in the cognitive sciences, which is the view promulgated by Fodor (1983), is too narrow. This narrowness derives, in part, from the use of strict analogies with computational systems as instantiated in digital computers. Because the mind is obviously not literally a digital computer, it is not surprising to find that little or nothing in the mind has properties identical to those of computer hardware. Here I argue that if the modularity concept is to have any value as a source of insight about functional specificity, we must realize that digital computers are just the source domain of a metaphor, and that *real* modules, in *real* brains, should be expected to do things differently. We must look for modules "in the flesh," not modules in the abstract, as defined in computer science, mathematics, or philosophy.

DEFINITIONAL PROBLEMS

Much of the divisiveness of the modularity debate has stemmed from people taking the modularity question as a yes–no question, to be settled using a set of criteria established by Fodor (1983). It is now recognized, however, that substantial problems with Fodor's criteria may make them inappropriate for mental modularity in general (Barrett, 2005; Barrett & Kurzban, 2006; Hagen, 2005; Pinker, 2005; Sperber, 1996, 2005). In particular, Fodor's criteria, because they were proposed for only one kind of system (input/peripheral/perceptual systems), may not be appropriate for all brain systems.

Fodor reasoned that the problem faced by perceptual systems is to make correct inferences about the structure of the outside world from perceptual inputs. Based on this analysis, he proposed that input systems should operate automatically and should not be influenced by "beliefs" or inputs from other systems. He characterized modules as rigid, innately specified, hardwired pipelines bringing information to central systems (Barrett, 2005; Fodor, 1983).

Although these criteria could be useful for some low-level perceptual systems, they might apply rarely, if at all. Take, for example, Fodor's (1983) criterion of dissociation or "characteristic breakdown patterns." In real life, brain damage almost never produces clean breaks between systems (Shallice, 1988). The sloppiness of the breaks, even when they are directional, is often taken as evidence against distinct systems (Uttal, 2001). Another key property, "encapsulation," refers to the inaccessibility to other systems of computational processes that occur within modules (Fodor, 1983). This property might also be far from absolute in specialized brain systems, whose processes might be designed to interface and interact with other systems in principled ways. Empirically, we know that brain systems are densely interconnected rather than isolated (Van Essen, Anderson, & Felleman, 1992), so few systems are likely to be "informationally isolated" in the way that most cognitive scientists think about modules. However, this does not mean that they are not functionally specialized.

THINKING LIKE A BIOLOGIST

When a biologist looks at living things, he or she sees modularity everywhere: "Modular organization, like plasticity, is a universal property of phenotypes, the result of the universally branching nature of development" (West-Eberhard, 2003, p. 56). The modularity concept in biology shares something with Fodor's (1983) notion. Discreteness or chunking of the phenotype and underlying developmental processes is an important aspect of the concept, but it is also recognized that the concept must tolerate the fact that "everything is connected," and that features such as plasticity are *aspects* of modules, not at odds with them (West-Eberhard, 2003). West-Eberhard (2003) points to the bones of the vertebrate skull as an example: They are modular, and homologies between bones in different taxa can be established, yet the positions of sutures can vary across individuals within a species, and how they appear in the phenotype depends on complex interactions between the modules during development. One can imagine further analogies. For example, even though not all breaks are cleanly between modular bone components, the patterns, although noisy, might tell us something about the underlying modular structure.

It is possible, of course, that the human brain is not modular in any useful sense, or that it is only crudely modular, with large sections, such as the cortex, being essentially unstructured. Fodor (1983) has suggested that only peripheral or "input" systems are modular, and that the structures responsible for "higher" cognition—those parts of the mind responsible for reasoning, judgment, and decision making—are decidely unmodular. Fodor's definition of "modularity" is such that this becomes true virtually by definition. For example, one of his criteria for modularity is that stimuli are processed "automatically," and processing cannot be interfered with by contextual factors in stimulus presentation. By this criterion, "higher" cognitive processes, which are notoriously prone to context effects, are ruled out: For example, framing effects in judgment and decision making (Tversky & Kahneman, 1981) could not be the result of modular systems. But does this mean that the systems involved in judgment and decision making are not functionally specialized? This seems an odd conclusion to make, at least on the grounds of framing effects alone.

Here, again, it is useful to look to biology. Biologists do not endorse a single checklist of properties that is associated with functional specialization in all contexts. Instead, biologists argue that the core of specialization in biological systems is the fit between *form* and *function* (e.g., Allen, Bekoff, & Lauder, 1998). If the function of judgment and decision-making systems is to guide behavior flexibly in diverse contexts, we might expect these systems *not* to be structured such that they inflexibly and automatically produce the same outcome in all situations, regardless of context. To take another example, isolation of brain systems from each other might make sense for perceptual systems whose function is to produce rapid interpretations of stimuli with a minimum of information, but the form–function match of such a design would be poor for systems such as those responsible for mate choice, which would be expected to integrate information from many sources, over a longer timescale.

MODULES MADE OF MEAT

The use of metaphors from computer science and computational theory has led to enormous progress in the cognitive sciences. In particular, the equation of neural processes with algorithms allows us to bring to bear the formal apparatus of computation theory in logic and mathematics, with its enormous generative power (Fodor, 2000; Marr, 1982). However, metaphors can have costs. In particular, it is true of all metaphors that only some mappings between source and target domains are valid. The computational metaphor invoked by Fodor and others makes assumptions that are appropriate for silicon-based computers, but that might not be appropriate for all neural computational systems. For example, although the modules in computer software and hardware are often truly "encapsulated" in Fodor's sense (i.e., interfaced with only via their inputs and outputs), they are also sometimes (and partly as a consequence of this) truly dissociable, in that they can be cleanly removed, or snapped in or out, without causing a system crash or noticeably impacting the operation of other systems. Often these features exist because of the explicit intentions of a programmer (e.g., to buffer against system failure, or to allow code to be easily modified).

There are many places where this metaphor fails when applied to brains. For example, constraints on human programmers are not necessarily constraints on evolution. A new mutation may have a large number of complicated nonlinear effects, but their fitness impacts are not contingent upon "understanding" them by any agent. Unlike software or hardware, brains are not designed in a top-down fashion, but rather evolve through accretion of small changes. If brain processes contain subroutines, they probably differ from "snap-in" software modules in many ways.

Unlike silicon-based computers, minds are, as Minsky put it, "computers made of meat" (or, more accurately, neural tissue) (cited in Gardner, 2002). Turing's (1936) demonstration of the formal equivalence of computational systems is often used to dismiss the importance of this fact. However, features such as encapsulation may sneak in constraints from the Turing model—such as the serial nature of operations and the need for systems to "take turns" in accessing information—that are not constraints on neural systems and, therefore, make a difference relative to how brains actually do things.

TAKING THE ORGAN METAPHOR SERIOUSLY

Chomsky (1988) famously compared modular brain systems to organs. According to this metaphor, the brain is not a single organ but many organs. Often, the more biological side of the metaphor—what it might imply about development, plasticity, and even computational properties—is disregarded in favor of focusing on "innateness." But given that the brain really *is* a biological organ, what if we took the organ metaphor seriously?

Developmentally, organs arise much differently than do computer programs. For example, the fact that modules "emerge" through dynamic processes during development is not, as some have claimed, an alternative to an evolutionary view (e.g., Smith & Thelen, 2003). Similarly, the way in which modules might be "coded for" in the genome is not literally equivalent to the way that software modules are "coded for" in programming languages (Marcus, 2004). Any notion of modularity that is to survive as a scientific concept must be biologically realistic.

In terms of information processing, the architecture of modular brain systems is likely to differ substantially from that of computers. For example, conventional computers route information through a central processing unit (CPU), whereas information processing in brains is massively parallel and decentralized, yet still produces functional outcomes. Therefore, we must look to models in which processing can occur locally, in the absence of central control, but in which local elements can also interact in a functionally effective manner. In a recent paper, I explored one such model based on an analogy to enzymes (Barrett, 2005; see also Sperber, 1996).

THE ENZYME MODEL

Enzymatic systems have several features that may offer a useful model of how modular processing of information could occur in an open, decentralized system. In the enzyme model of cognition, the matching of inputs to procedures is done via a recognition process on analogy to substrate binding, which involves fuzzy parallel feature recognition, as in neural network categorization systems. The computation itself is a mapping of substrates to products, which are then made available to other systems.

Two features of enzymatic computation systems that may have important parallels to real brain systems are massive parallelism and self-selection. In Fodorean modular systems, information is routed to proprietary systems only, as if via pipes. In a "bulletin board" style enzymatic system, products are publicly broadcast, and selective processing is handled by the lock-and-key nature of substrate recognition. Self-selection may be an important feature of specialized processing at all levels of brain organization, because it obviates the need for a supervisor or prewired pipelines. Increasingly, the advantages of systems in which many "demons" or subroutines operate in parallel, interacting dynamically (competitively or cooperatively) to create emergent global organization, are being recognized (Holland, 1995; Minksy, 1987; Selfridge & Neisser, 1960). Other features of the enzyme model, such as tagging or modification of representations for consumption by other systems, modulation of activity between systems, by-product processing (as in metaphor), adjustment of processing via top-down feedback, and competition for processing based on goodness of fit, may also have analogies in real brain systems.

LOOKING FOR ANSWERS IN THE BRAIN ITSELF

It is clear that we cannot answer questions about modularity without deciding how we would know a module when we see it. Fodor's criteria are problematic, because they may match nothing in the brain when pushed to the

limit, and because they were derived from design considerations based on problems faced only by some parts of the brain. Applying design criteria from one kind of system to another can be a major mistake. "Central" systems for planning, inference, and decision making face quite different problems than do perceptual systems, and so might have very different design features, such as integrating rather than excluding information, but may nevertheless be modular.

As elsewhere in biology, we must be prepared to be flexible in our use of the modularity concept, and most importantly, to know *why* we are invoking the concept. If we are looking for functionally specialized structures, we must be prepared to take the idea of structure–function correspondence seriously. The blind search for properties such as encapsulation or insensitivity to developmental environment makes no sense from this perspective. We should be prepared to let the brain inform us about how it solves problems, rather than deciding in advance.

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