Title
The Future of Modularity

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This symposium focused on the role to be played by notions of modularity in the field of cognitive science. Modularity has exhibited several different construals in various areas within the cognitive and neural sciences. It has been applied in language research as a *strict* encapsulation of information (Forster, 1979). It has been employed in defining the initial stages of a fuzzy logical model of information *integration* (Massaro, 1989). It has been split into notions of *representational* versus *processing* modularity (Tanenhaus, Dell & Carlson, 1987). It has been used to partially constrain *interactive* connectionist networks (Jacobs, Jordan & Barto, 1991). It has been loosely accepted in visual neuroscience as a catch-phrase for brain structures that are *mostly* specialized for certain subdomains of information (Lennie, 1996). And, finally, it has been criticized entirely as encouraging oversimplified, and sometimes misleading, "descriptive conveniences" (McClelland, in press).

This symposium brought together proponents of the disparate perspectives on this issue (as well as those who walk the fence between these extremes) in hopes of making progress toward a more unified view of 1) the definition of modularity, and 2) its account of cognitive and perceptual phenomena. To ensure applicability to a wide audience, an emphasis was placed on general theoretical accounts.

Questions Addressed in this Symposium

- How does modularity constrain scientific inquiry?
- What is the difference between encapsulation and specialization?
- Should we think about modularity differently for cognition than for perception?
- Are non-modular systems intractable?
- What aspects of the modularity hypothesis have withstood empirical study?
- Should we, and if so how would we, redefine modularity?

The Continuum of Modularity

In 1983, Fodor offered persuasive (though not demonstrative) arguments that the remarkable speed with which linguistic and perceptual processing occur necessitates their possessing at least three essential properties: domain specificity, mandatoriness, and information encapsulation. According to Fodor, these properties distinguish the rapid processing in these specialized "modular" systems from the typically slower and rather amorphous processing of general cognition, which integrates the modules' outputs to achieve the individual's goals. In the 1980s, this view of the mind/brain was clearly antithetical to the emerging interactive, connectionist view. Whereas modularity considered the integration of multiple sources of information to be incompatible with rapid processing, the interactive view saw integration as primarily responsible for it.

In recent years, however, the theoretical distinctions between modularity and interactionism have become increasingly vague and indeterminate (cf. Boland & Cutler, 1996; Karmiloff-Smith, 1992). This is because technological advances have provided more precise and informative measures (e.g., eye-movement monitoring, neuroimaging, etc.) for testing the views' contrasting predictions. This has led to both modular and interactive models becoming more explicit in their architectural assumptions, and as a consequence, their differences are now diverse and often subtle. In particular, while a number of different dimensions are considered to instantiate modularity, no single dimension is definitive. Moreover, the particular value on a dimension that is used to typify modularity can differ from one research domain to another. For example, "modular" models of vision tend to process information via *parallel* pathways, whereas "modular" models of language tend to process information in *serial* stages.

At least three other dimensions are relevant for distinguishing between modularity and interactionism (see Figure 1). Like parallel-serial, *bidirectional-unidirectional* relates to processing assumptions. Models that assume strictly feedforward information flow are typically classified as modular, while those that permit bidirectional flow (recurrence) are often classified as interactive. The other two dimensions relate primarily to representational assumptions. Models employing *symbolic* representations are more likely to be considered modular than models employing *distributed* representations. And models that assume *binary* activation values (single representational output) are frequently viewed as modular, whereas those that assume *probabilistic* activations (multiple representational output) are typically viewed as interactive.

Figure 1 depicts these dimensions as a four-dimensional space, and modularity is conceptualized as a continuum (represented by the dashed diagonal) that extends through the center of this space. When a model is specified in enough detail to be associated with a region in this space, that region's projection onto the continuum of modularity

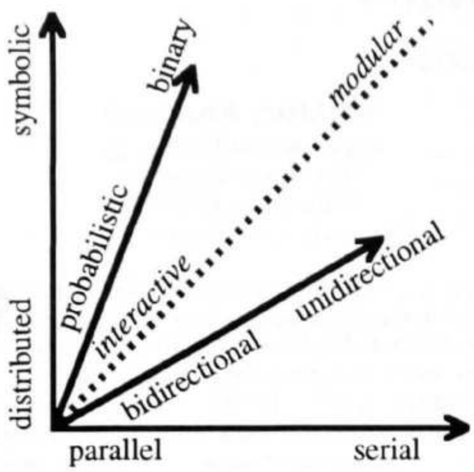

Figure 1: 4-D modularity space, in which various models look more modular or less modular than one another, but in which a true dichotomy of "interactive *or* modular" does not exist. The dashed line represents the continuum of modularity.

indicates the *degree to which* the model is modular. Thus, according to this conceptualization, modularity is not an all-or-none feature of human information processing systems.

It seems that much of the debate (both within and across domains) over the modularity of the mind/brain stems from differences in which dimensions in this 4-D space are emphasized. For example, one might implicitly accept a model with *serial stages* (e.g., a stage in which representations are accessed, and ambiguity arises, followed by a stage in which one is selected, and ambiguity is resolved) and strictly *feedforward processing* (i.e., constraints that affect a later stage like selection cannot affect an earlier stage like access) (Boland & Cutler, 1996). While these features give the appearance of complete modularity, if the model incorporates an interactive feature (such as probabilistic representations, or multiple-output), then it will not be categorically "modular."

Clearly, both perceptual and linguistic processing are rapid and often mandatory. And, consistent with modularity's requirement of domain specificity, there is evidence that the underlying cortical structures exhibit some degree of independence (e.g., Shallice, 1988). However, contrary to modularity's requirement of information encapsulation, there is compelling evidence for recurrent connections between cortical structures (e.g., Sejnowski & Churchland, 1989) as well as for the computation of vastly distributed representations or "population codes" (e.g., Georgopoulos, Taira, & Lukashin, 1993). Thus, the most accurate view of the mind/brain probably lies on the middle ground of modularity and interactionism.

The Future

Redefining modularity as a continuum radically affects its fundamental tenets. By allowing its characteristics to be graded rather than absolute, its ability to "constrain scientific inquiry" is severely compromised. Moreover, as models become more recurrent and less unidirectional, they blur the distinction between perception and cognition (and action). Conversely, as models approach the extreme in interactionism, incorporating richly distributed representations and nonlinear temporal dynamics, they can become opaque and unfalsifiable. Thus, the challenge for the Continuum view is to construct explicit models that generate testable, coherent predictions.

One important advantage of the Continuum view is that, contrary to Fodor's (1983) claims, general cognition *is* within the realm of scientific investigation. This is important because the vast majority of behavioral measures in cognitive science necessarily reflect the operation of general cognition. Thus, ironically, if modular input systems are viewed as completely encapsulated, *they* are the mental constructs that are less amenable to scientific study (barring the use of neurophysiological techniques). Furthermore, because modularity considers subjects' goals and expectations as contaminating the measurement of modular processes, it encourages studying the processes in highly decontextualized situations. As a result, subjects' goals are often uncontrolled, thus introducing substantial variability in the data. In contrast, the Continuum view considers subjects' goals as crucial factors that affect processing efficiency. Because these effects can, and should, be directly measured, this view encourages highly contextualized experimental situations that create well-defined behavioral goals. Thus, the Continuum view sets a new and, we believe, more fruitful agenda for future research.

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