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Defining an Ontology of Cognitive Control Requires Attention to Component Interactions

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Abstract

Cognitive control is not only componential, but those components may interact in complicated ways in the service of cognitive control tasks. This complexity poses a challenge for developing an ontological description, because the mapping may not be direct between our task descriptions and true component differences reflected in indicators. To illustrate this point, I discuss two examples: (a) the relationship between adaptive gating and working memory and (b) the recent evidence for a control hierarchy. From these examples, I argue that an ontological program must simultaneously seek to identify component processes and their interactions within a broader processing architecture.

Keywords: Cognitive control; Prefrontal cortex; Executive function; Working memory

A strength of cognitive neuroscience is its ability to test whether proposed distinctions among psychological constructs are supported by corresponding distinctions in the brain, and conversely whether constructs thought to be unitary are actually componential. In this respect, the cognitive neuroscience approach is ideally suited for addressing the question of whether cognitive control is componential. The innovative approach taken by Lenartowicz et al. (2010) formalizes this logic, and so most directly addresses the question of where true processing distinctions lie among classes of cognitive control tasks. Taken together with the evidence reviewed in the other target articles, it seems clear that not only is there a specialized system for guiding behavior based on our goals, plans, and context but also that this system has separable components that contribute individually to task performance and rely on separable neural systems. However, across the target articles, it also is striking that though each argues effectively for component processes, the component processes being discussed are qualitatively different from article to article with relatively little overlap. This is not unique to this sample of papers and is not unlike the cognitive control literature,

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generally. Indeed, to define a cognitive control ontology is to determine which distinctions drawn in the cognitive control literature are real and which are not.

However, in building our cognitive control ontology, it is perhaps worth remembering that our understanding of our data is only as good as our task analysis. More specifically, though we measure the correlates of cognitive processes in behavior or in neuroimaging, we intervene indirectly on those processes via a task manipulation. Hence, we do not actually know that the task comparisons we employ isolate one and only one cognitive process, such as response selection or response inhibition. And, even if we were to have such a pure contrast, we cannot be sure that our descriptive label for this process is the best characterization of its actual computational goal. For example, inhibition tasks might tend to tax monitoring or salience processing more than other tasks (e.g., Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010), and so without direct controls, indicators associated with monitoring during inhibition tasks would masquerade as indices of inhibition processes. Likewise, there may be complex interactions among component processes themselves, making the direct causal mapping between the label given to a task manipulation and the process reflected by a pattern of brain activation more difficult to infer. In what follows, I will briefly argue from two examples that this type of complex componential structure is not merely an abstract possibility, but indeed may be the way that cognitive control is organized, and so demands an approach that focuses simultaneously not only on components but also their putative interactions.

Computational modeling is a powerful means of formalizing hypotheses regarding the latent processes that are active during cognitive control tasks (Alexander & Brown, 2010; Cohen, Dunbar, & McClelland, 1990; O'Reilly & Frank, 2006; Yeung, Cohen, & Botvinick, 2004). As reviewed by Alexander and Brown (2010), often these models have identifiable components, such as conflict monitoring or outcome prediction. However, in these cases, cognitive control emerges from interactions among these processes as subcomponents of a larger network carrying out a range of ''executive functions'' from inhibition to set shifting.

Consider, for example, the putative distinction between ''working memory'' and ''adaptive gating.'' Several models of cognitive control rely on a biased competition framework, whereby contextual representations maintained in working memory bias relevant action pathways over irrelevant, habitual ones (Desimone & Duncan, 1995; Miller & Cohen, 2001; O'Reilly & Frank, 2006). For example, in the Stroop task, maintaining the task goal ''color naming'' in working memory biases selection of the mappings from ink colors to responses rather than words to responses (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen et al., 1990). This working memory function is typically attributed to PFC (MacDonald, Cohen, Stenger, & Carter, 2000). So, from this perspective, PFC carries out a working memory function, but in the service of cognitive control more generally; in this case, overcoming color word interference via response selection and/or inhibition.

Importantly, this type of active maintenance requires some means of opportunistically updating working memory with relevant information when it becomes available, and conversely, keeping out irrelevant information (Braver & Cohen, 2000; Hazy, Frank, & O'Reilly, 2007). In other words, working memory requires some form of adaptive gating. Several models have implemented gating as an independent component from working memory (Brown, Bullock, & Grossberg, 2004; Hazy et al., 2007; O'Reilly & Frank, 2006). Indeed, theoretical work has indicated that recurrent networks benefit from having a gating system as a separate component that aids in input and output selectivity (Hochreiter & Schmidhuber, 1997).

Consistent with these models, evidence has implicated the striatum in supporting a gating function in order to update working memory representations maintained separately in PFC (McNab & Klingberg, 2008). And, moreover, this distinction has been shown to account for individual differences in behavior, such as those arising from genetic differences thought to differentially affect striatal versus prefrontal dopamine (Frank, Doll, Oas-Terpstra, & Moreno, 2009; Frank, Moustafa, Haughey, Curran, & Hutchison, 2007). To summarize, then, there is evidence that working memory and adaptive gating are separate components supported by separate neural structures, which can be studied individually, and give rise to individual differences in behavior. However, they do not readily correspond to executive functions expressed at the task level, like inhibition or task switching. Rather, they are subcomponents, each with its own computational goal. Their cognitive control function, then, is only meaningful in the context of their interaction with each other and a broader control architecture. This example cautions against reifying tasks or necessarily expecting componentiality to emerge as a toolbox of executive faculties. However, to be clear, separate adaptive gating and working memory functions are fully consistent with a componential view of cognitive control. Thus, differences among such subcomponents are testable using classical cognitive neuroscience methods and verifiable using meta-analysis approaches such as that proposed by Lenarkowitz et al. (2010).

The story becomes further complicated if one considers that latent processes, though separable, may nevertheless interact in complex ways given a particular task. One example of this comes from recent evidence, also touched on by Stout (2010), indicating that separable pools of neurons from rostral to caudal frontal cortex may interact with each other asymmetrically from front to back in the service of cognitive control (Badre & D'Esposito, 2009; Koechlin & Summerfield, 2007). Growing evidence has indicated that as demands on cognitive control processing become more abstract, separable regions in more rostral portions of frontal cortex are engaged (Badre & D'Esposito, 2007; Koechlin, Ody, & Kouneiher, 2003). Though abstraction has been defined differently across these cases (e.g., Badre, 2008), a general claim is that this gradient reflects a control hierarchy whereby processing in more rostral regions influences processing in caudal regions more than vice versa (Badre & D'Esposito, 2009; Koechlin et al., 2003). Some evidence exists for this asymmetric flow of processing from effective connectivity analysis of fMRI data (e.g., Koechlin et al., 2003). However, recent data from patients with damage to regions along the rostro-caudal axis of frontal cortex perhaps provides a more direct demonstration (Badre, Hoffman, Cooney, & D'Esposito, 2009). In particular, damage at a given point along frontal cortex leaves cognitive control tasks intact that require only regions caudal to the lesion (i.e., more concrete control) but impairs any tasks requiring regions of PFC rostral to the lesion (i.e., more abstract control). This asymmetric pattern of deficits presumably arises because of the front to back processing interactions among these regions.

An important implication of this asymmetry is that separable indicators of these independent processes can be masked in many tasks because all tasks that require rostral regions also require caudal regions, but not all tasks that require caudal regions require rostral regions. To account for this bias, we tested task performance across conditions of an abstract control task after accounting for impairments due to deficits at more concrete levels of cognitive control (i.e., supported by more caudal regions of PFC). Correcting for the asymmetric interaction between component processes produced a cross-over interaction between patient groups, and so provides evidence of separable control processors at different levels of abstraction (Badre et al., 2009). Analogous logic can be used to produce dissociations in fMRI activations along rostro-caudal frontal cortex (Badre & D'Esposito, 2007). Thus, as this example illustrates, a failure to account for interactions among processors can mask true distinctions where they exist. Thus, understanding the dynamics among processors may be a necessary precondition for designing experiments capable of distinguishing separate components in our ontology.

Cognitive control, and the neural systems that support it, are componential. However, componentiality can be real and even demonstrable in behavioral and neural differences without it corresponding to a toolbox of encapsulated executive faculties that directly correspond to qualitative task descriptions (like inhibition or task switching). Indeed, the evidence is strong that in some cases distinctions in various indicators emerge from the differential contribution of separable, but interacting subcomponents (like working memory and adaptive gating) under distinct task demands. Similarly, interactions among these subcomponents can mask true component distinctions where they exist, as with asymmetric interactions among control processors along rostro-caudal frontal cortex. Cognitive neuroscience is undoubtedly important in moving us toward an ontology of cognitive control, and approaches like that introduced by Lenartowicz, Kalar, Congdon, and Poldrack (2010) are a powerful means of formalizing this process. However, an ontological program should seek to find a set of component processes that is sufficient to account for the indicators under study while also being explicit about how these components interact with each other within a broader processing architecture.

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