Understanding interactions amongst cognitive control, learning and representation

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Introduction

Research in cognitive control investigates how cognition and behavior get tailored to suit behavioral goals in particular task contexts. The work often focuses on mechanisms that adjudicate competition amongst simultaneously active but mutually incompatible representations. The objects of control—the competing representations—are often cast as fixed entities: control influences interactions among these but does not shape the representations themselves. Conversely, research into the origins of mental representations (perceptual, linguistic, semantic, etc.) often neglects questions central to theories of control: whether and how the acquired representations support flexible task-dependent behaviors, the degree to which learning produces representations that compete or cooperate within and across tasks, or the extent to which learned representations require task-dependent potentiation to operate effectively.

Recent work within each tradition suggests, however, that control, learning, and representation are tightly interconnected. First, the degree to which control is required for any given task and stimulus domain depends critically on the nature, structure, strength, and compatibility of the underlying representations, which in turn arise from learning and experience. Second, when the same items are engaged in a variety of different tasks, it may be useful to exploit a common representation across tasks, or to learn different representations for each, or to find some middle ground—thus learning must produce a flexible set of representations suited to control demands and capturing shared structure within and across task contexts. Third, since control shapes the flow of activation within sensory, motor, and associative systems, it must also constrain activation-dependent learning within and between these systems—that is, the representations acquired must depend to some degree upon control.

This symposium brings together four perspectives on the mutual constraints existing among systems of control, learning, and representation. In each case, consideration of these mutual influences leads to new and often surprising resolutions to long-standing questions across seemingly disparate domains of cognitive neuroscience.

The rational boundedness of cognitive control: Shared versus separated representations

Sebastian Musslick, Abigail Hoskin Novick & Jonathan D. Cohen, Princeton University

A fundamental and striking limitation of human cognition is the constraint on the number of control-dependent processes that can be executed simultaneously, which forms one of the most basic and influential tenets of cognitive psychology: controlled processing relies on a central, limited capacity processing mechanism that imposes seriality on control-dependent processes. We present a challenge to this view that distinguishes control-dependent and automatic processing by their reliance on shared vs. separated representations. Specifically, we propose that: task performance relies on sets of representations that may be shared with others; the inability to perform more than one task at a time may reflect conflict that arises when the tasks involved make use of the same set of representations for different purposes; and the purpose of control is to prevent such conflict by restricting use of such shared sets of representations to just one task at a time. That is, constraints associated with control-dependent processing reflect a rational response to sharing of representations, rather than limitations in the control mechanism itself. We use graph-theoretic methods to formalize this theory, and analyze the multitasking capability of two-layer neural networks when representations are shared/not shared across tasks. The multitasking capability of a network drops precipitously with an increase in shared representations, and is virtually invariant to network size.

Why then should a network use shared representations at all? In computational simulations and behavioral experiments we demonstrate a tradeoff between learning efficiency, promoted by shared representations, and multitasking, best achieved via separated representations. The commonly-observed trajectory from controlled to automatic processing may therefore reflect an optimization of this tradeoff: shared representations initially afford a bias toward efficient learning in novel task environments at the expense of seriality and control-dependence; but experience in environments where multitasking affords sufficient advantage ultimately promotes acquisition of separated, task-dedicated representations.

Canonical representations for generalization in relational reasoning

Taylor Webb, Steven Frankland, Alexander Petrov[1], Randall C. O'Reilly[2] & Jonathan D. Cohen, Princeton University, Ohio State[1], and U. Colorado-Boulder[2]

The preceding talk suggests that capacity limits on control-dependent tasks fundamentally arise from the use of shared representations across tasks. Why then should cognitive systems employ shared representations? The answer may lie in the remarkable human capacity to generalize far beyond the scope of experience. By contrast, state-of-the-art neural network algorithms tend to do well at interpolating between data points in their training corpora, but generally fail to extrapolate beyond the scope of those data points.

We propose that one way to enable human-like generalization in neural networks is by giving them access to a basis set of canonical, general-purpose representations that capture the abstract relations inherent in common structural motifs (e.g. lines, rings, or trees). We present a method for transforming domain-specific representations into a canonical form, and show that these transformed representations enable robust extrapolation to data points far from the training domain — that is, out of domain generalization. Such broad generalization requires, however, that processes within and across task and item domains share use of the canonical representations, thus making them dependent on control. Understanding the conditions under which canonical representations arise thus provides insight into both the human capacity for generalization and the relationship of this ability to cognitive control.

Toward a neural architecture for controlled semantic cognition

Rebecca J. Jackson, Timothy T. Rogers & Matthew A Lambon Ralph, Cambridge University

We consider how opposing demands of task-specific control versus broad generalization might constrain the architecture of the networks that support semantic cognition—the remarkable human ability to flexibly deploy conceptual knowledge across a variety of behavioral contexts. The semantic system must acquire context-invariant representations that express conceptual structure by abstracting over episodes, time, and modality (sensory, motor, linguistic, and affective), while also dynamically tailoring representations to produce context-appropriate similarity structures and behaviors. How should a semantic system be structured to promote both functions?

We report simulations with models varying in five architectural features, representing different hypotheses about the influence of control on semantic processing and the structure of the semantic network itself. We compared model variants in their acquisition of both context-invariant conceptual structure and context-dependent tailoring of representations and outputs. The system's functioning was best served by an architecture employing a single, deep multimodal hub containing sparse long-range connections from modality-specific inputs, and with control systems operating on peripheral modality-specific representations without affecting the hub. This architecture creates regions of relative specialization for control and representation, explaining distinct patterns of semantic dysfunction arising from temporal versus fronto-parietal pathology. The simulations thus suggest that the cortical anatomy of semantic cognition can be understood as balancing demands of representation and control.

Learning, control, and modularity in lexical semantics.

Lang Chen, Stanford University
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A central goal for cognitive approaches to language has been to understand whether various sub-processes operate independently or are mutually interdependent. In accordance with the preceding talks, we suggest the tension between views can be resolved by considering how cognitive control and task-specific experience jointly impact learning in lexical semantic systems, taking visual word recognition as a well-studied example of the controversy. On one hand, patients with acquired semantic impairments typically show difficulty recognizing low-frequency words with unusual orthography, suggesting an interdependence between lexical and semantic representations. On the other, a handful of cases show serious semantic impairment with normal word recognition, suggesting that recognition and semantic processes are independent. Similar patterns in other aspects of language have produced fundamentally different perspectives: one in which all varieties of linguistic representation mutually constrain one another, and another in which different representations are modular and independent.

We show that lexical and semantic representations in a recurrent neural network can become modular when (1) words appear in task-contexts requiring independent activation of each representation and (2) a context-dependent control signal strongly constrains activation in the network. This model suggests that individuals with strong executive control and unusually frequent experience with orthography may develop relatively independent lexical and semantic representations. We tested this hypothesis using dual-task studies to assess semantic interference on word recognition. Most participants showed degraded recognition with concurrent semantic processing but a small percentage showed no such effect. These exceptions uniformly showed exceptional orthographic knowledge and no interference in a Stroop task—suggesting that strong control and practiced orthography jointly promote independent lexical and semantic processing. The results offer a middle ground between fully modular and fully interactive perspectives, and suggest that control and learning play critical roles in shaping the degree to which various linguistic representations interact.