Toward a Unified View of Cognitive Control

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Abstract

Allen Newell (1973) once observed that psychology researchers were playing "twenty questions with nature," carving up human cognition into hundreds of individual phenomena but shying away from the difficult task of integrating these phenomena with unifying theories. We argue that research on cognitive control has followed a similar path, and that the best approach toward unifying theories of cognitive control is that proposed by Newell, namely developing theories in computational cognitive architectures. Threaded cognition, a recent theory developed within the ACT-R cognitive architecture, offers promise as a unifying theory of cognitive control that addresses multitasking phenomena for both laboratory and applied task domains.

Introduction

Almost 40 years have passed since Allen Newell's seminal "twenty questions" paper (Newell, 1973) in which Newell expressed both optimism and concern about the state of cognitive psychology research. Newell noted that a great deal of work had gone into gathering rigorous empirical data and developing creative theories for tens if not hundreds of psychological domains, but this work had also raised a deeper underlying concern: how exactly can these individual lines of research help to achieve a grand understanding of human cognition? One might ask very much the same question about the many interesting lines of research on cognitive control in progress today. Certainly this work augments our knowledge of the phenomena surrounding cognitive control, and articles in the special issue highlight cognitive control's connections to language (Cragg & Nation, 2010), evolution (Stout, 2010), and consciousness (Mandik, 2010). Nevertheless, we may justifiably be concerned with how these individual pieces fit together—how they influence one another, and more deeply, how they all may arise from the same core human system, as we know they must.

Consider for example two domains described by Cooper (2010): task switching and dual choice. Task-switching research, using alternating execution of two simple tasks, has highlighted the temporal "switch cost" incurred when enacting a task switch (e.g., Monsell, 2003). Dual-choice research, using concurrent execution of simple tasks, has highlighted the presence of a central cognitive bottleneck in multitasking (e.g., Pashler, 1994). Interestingly, it has been shown that under certain conditions, people can achieve "perfect time sharing"—performing two concurrent choice tasks as fast as performing each choice task independently (Schumacher et al., 2001). What is the relationship between switch costs in the task-switching paradigm and the cognitive bottleneck in the dual-choice paradigm? Why can switch costs disappear under some dual-choice conditions after practice?

Taken more broadly, Newell's concerns can be extended to linking our understanding of cognitive control to the real world. The classic task-switching paradigm uses the same stimulus for two different tasks. When considered in the real world, such as the many recent studies of human-computer interaction (e.g., Bailey & Iqbal, 2008), task switching almost never involves the same stimulus or task environment. We might then justly question the generality of such paradigms to the real world: What does an understanding of switch cost in classic task switching tell us about temporal costs incurred in (say) forced or self-imposed interruptions while writing a document or sending electronic mail? What does an understanding of cognitive bottlenecks in simple choice tasks tell us about potential cognitive interference in continuous, complex tasks like driving (Strayer & Drews, 2004)?

Cognitive Control in a Computational Cognitive Architecture

We share Newell's view that the best way to explore these connections involves the development of unified theories of cognition, particularly as instantiated as a computational cognitive architecture (Newell, 1990). In this spirit, we have developed a theory of cognitive control and multitasking, threaded cognition (Salvucci & Taatgen, 2008, 2010), within the framework of the ACT-R cognitive architecture (Anderson, 2007). Threaded cognition posits that the human control system centers on concurrent "threads" of cognitive processing that enable multitasking performance but also can experience multitasking interference among its cognitive, perceptual, and motor resources. The core idea is that multiple threads or goals can be active at the same time, and as long as there is no overlap in the cognitive resources needed by these threads, there is no multitasking interference. When threads require the same resource at the same time, one thread must wait and its performance will be adversely affected.

In threaded cognition, task control emerges from the interaction between threads and cognitive resources, and therefore aligns best with Cooper's (2010) "emergent" view of control. Because multiple threads can be active at the same time, the theory predicts that there are normally no switch costs between tasks, as would be the case in perfect time-sharing; however, overlapping use of cognitive resources normally results in interference, as is the case for dual-choice tasks (see Salvucci & Taatgen, 2008). The task-switching paradigm, however, presents a degenerate case, infrequently seen outside the laboratory, in which the mapping between a stimulus and its associated task is ambiguous. In this case, a deliberate strategy must be used to keep the threads apart by strategically initiating and suspending threads to ensure that only one of them is active at a time.

Even under this emergent view, ACT-R and threaded cognition allow for task-specific components and constraints to guide cognitive control. At first, one might imagine a high-level general controller that schedules and prioritizes cognitive resources, much like Norman and Shallice's (1986) supervisory attentional system. While Shallice and others have worked toward this goal (see the summary in Cooper, 2010), a rigorous computational specification of such a system has proven extremely difficult (Kieras et al., 2000). A different view, more in line with threaded cognition, is to consider how task-specific knowledge may allow a task thread to modulate its own resource usage. For example, a model of driving may relinquish visual and/or cognitive processing in less challenging environments, thus freeing up resources that might be used for other tasks (e.g., setting the radio); an ACT-R model of such a task can then predict potential interference throughout the modulation process (e.g., Salvucci, Taatgen & Kushleyeva, 2006). In other words, multitasking behavior and interference can in part emerge from task-specific control aspects of particular task threads.

The unifying spirit underlying threaded cognition and ACT-R is perhaps most closely reflected in the target article of Alexander and Brown (2010) and their prediction of response–outcome (PRO) theory of control. However, their theory seems to be focused exclusively on human (and monkey) behavior in the context of controlled experimental settings. We believe that, going forward, theories of cognitive control will need to extend beyond the laboratory to applied complex domains, as Cragg and Nation (2010) illustrate for the domain of language development. The original description of threaded cognition (Salvucci & Taatgen, 2008) presented three models of driving and driver distraction that explored the implications of the theory on this important applied domain. More recently, we have explored the interaction between threaded cognition and Altmann and Trafton's (2002) memory-based theory of task switching as applied to realistic human-computer interaction (Salvucci & Taatgen, 2010). Altmann and Trafton's theory describes how cognition rehearses and resumes interrupted goals; when the rehearsal process is represented in terms of ACT-R memory theory (Anderson, 2007), threaded cognition specifies how rehearsal can be performed concurrently with the interrupting task. Such work illustrates the unifying spirit of this work and provides an essential complement to the accounts of behavior in laboratory tasks.

Like Newell (1973), we find ourselves half impressed and half concerned about the current state of cognitive control research: impressed by the rigor and scope of the empirical data available, but concerned by the relative lack of theories that strive to provide unified accounts of experimental and applied data, and that extend to tasks in which people outside of psychology are interested. Unified theories and more specifically computational cognitive architectures remain, in our view, the best way to understand cognitive control in the broader context of human cognition.

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