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Cognitive Control: Componential or Emergent?

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Abstract: The past twenty-five years have witnessed an increasing awareness of the importance of cognitive control in the regulation of complex behavior. It now sits alongside attention, memory, language and thinking as a distinct domain within cognitive psychology. At the same time it permeates each of these sibling domains. This paper reviews recent work on cognitive control in an attempt to provide a context for the fundamental question addressed within this Topic: is cognitive control to be understood as resulting from the interaction of multiple distinct control processes or are the phenomena of cognitive control emergent?

Introduction

Cognitive control refers to the processes or mechanisms invoked in generating or regulating behavior when that behavior goes beyond the application of learned stimulus-response associations. Consider a subject performing any standard psychology experiment where she/he must follow a set of apparently ad hoc instructions invented by the experimenter and relevant only for the duration of the experimental session. A “good” subject will ignore distractions, attend to the stimuli (which may well be entirely novel), and respond as instructed, perhaps adjusting behavior to fit some imprecisely specified criterion such as to respond as quickly and accurately as possible. Or consider an operator of a complex artifact such as helicopter, a nuclear power station, or even a video game. Here the operator must attend and respond to one set of stimuli (e.g., to maintain the status quo) while simultaneously monitoring for warnings or threats and responding appropriately if or when such threats arise. It is now commonly argued that the regulation of complex cognition, particularly in situations such as the above which entail the performance of concurrent and/or non-routine tasks, involves a set of conceptually distinct control (or “executive”) functions such as task setting, response selection and monitoring.

Within cognitive psychology the notion of cognitive control can be traced to long before the cognitive revolution, with Stroop’s color-naming task (Stroop, 1935) being the paradigmatic example of one whose difficulty lies in the need to inhibit a prepotent response.¹ Even before this, Jersild (1927) had investigated processes of switching between tasks – processes now considered to be control processes. More recently the work of cognitive psychologists has led cognitive neuroscientists to attempt to localize specific control processes to distinct neural structures or regions (e.g., the putative localization of inhibitory processes to right inferior prefrontal cortex: Aron et al, 2004). At the same time computationally explicit models of hypothesized control processes have been developed (e.g. Botvinick et al, 2001, on modeling the putative control process of conflict monitoring). Slightly further afield, theories of

¹ In the Stroop task, the subject is presented on each trial with a word printed in colored ink. The color of the ink varies across trials and the subject is required to ignore the word and name the color of the ink. There are three kinds of trial. Incongruent trials are those where the word is the name of a color that differs from the ink color (e.g., **RED** printed in blue ink). Congruent trials are those where they are the same (e.g., **BLUE** printed in blue ink). Neutral trials are those in which the “word” is either a non-word letter string (e.g., **TCLQ** printed in blue ink), a non-color word (e.g., **CAT** printed in blue ink), or a color patch. Typically responses are faster on congruent trials than on neutral trials (i.e., there is a facilitation), but slower on incongruent trials than on neutral trials (i.e., there is interference).

behavior control that are grounded in cognitive psychological theories of control have been implemented in both fixed (Kawamura & Gordon, 2006) and mobile robots (Chernova & Arkin, 2007), while in psycholinguistics it has been argued that cognitive control, and processes related to task switching and inhibition in particular, play a key role in the language processing of bilinguals (Bialystok & Viswanathan, 2009). Even in philosophy of mind the possible existence of such processes would seem to answer some thorny questions (by partially decomposing the homunculus of central cognition) but raise others (about how control processes are themselves controlled). However, despite this broad interest in mechanisms of control across many of the cognitive sciences, foundational issues concerning cognitive control remain unresolved. Most critically:

1. Is there a set of cognitive control processes that operate across domains (i.e., are they “componential”), or are cognitive control functions more correctly understood as emergent theoretical constructs with no causal or explanatory utility?
2. If cognitive control is componential, what control functions are there (or what are the criteria for proposing a control function), how are those functions cached out as processes or mechanisms and how do they interact in the control of specific tasks?
3. If control phenomena are emergent, how are the empirical effects which have been argued to support cognitive control functions (e.g., related to individual differences, dual-task tradeoffs, language processing in bilinguals, arbitrating between behaviors in cognitive robotics, etc.) to be explained?

It is these questions that motivate the debate expressed in the current Topic. This introduction provides some context for this debate by first reviewing the rationale for several commonly proposed control functions and then introducing the alternative hypothesis.

The Three Functions of Miyake et al (2000)

To illustrate the componential view of cognitive control, consider the widely cited study of Miyake et al (2000), who investigated three control functions – *response inhibition*, *task shifting* and *memory monitoring/updating* – which were held to be distinct based on previous work. Conceptually, response inhibition is the process of actively inhibiting a prepotent response. Task shifting consists of switching from one task with its associated stimulus-response associations to another task with a different set of stimulus-response associations. Memory monitoring/updating involves “monitoring ... incoming information for relevance ... and then appropriately revising the elements held in working memory” (Miyake et al, 2000, p 57). The study used an individual differences methodology with 137 subjects each completing nine simple tasks (including the Stroop task) and five more complex tasks, such as the Tower of Hanoi problem-solving task². Three of the nine simple tasks (including the Stroop task) were held to load primarily on response inhibition, three on task shifting, and three on memory monitoring/updating. Performance on the five more complex tasks was held, potentially, to involve multiple control processes.

In the first phase of the analysis, the authors used the statistical method of confirmatory factor analysis to argue, from inter-task correlations among the nine simple tasks, that the three control functions of interest were correlated but separable. Thus, the data was well accounted

² In the Tower of Hanoi task, the subject is presented with an apparatus consisting of three vertical pegs with three (or more) disks of different sizes stacked on the pegs such that no disk sits directly above a larger disk. The subject is shown a target configuration of the disks, and is required to rearrange the disks so as to achieve the target configuration, subject to the constraint that only one disk can be moved at a time and a large disk cannot be placed on a peg if it is occupied by a smaller disk.

for by a three-factor model with performance on the three response inhibition tasks loading on one factor, performance on the three task shifting tasks loading on a second factor, and performance on the three memory updating/monitoring tasks loading on a third factor. Moreover, the three factors were found to be moderately correlated, suggesting that while they did not reflect a unitary construct neither did they reflect the operation of three fully independent processes. Critically the authors also showed that a variety of other models – models with one factor, with three independent factors, or with two factors in which two of the three putative control functions were equated – produced statistically less adequate accounts of the data for the simple tasks.

The first phase of Miyake et al's (2000) analysis effectively produced, for each subject, an "inhibition" score, a "shifting" score, and an "updating" score. In the second phase of the analysis these scores were used, following the procedures of structural equation modeling, to compare different statistical models of performance on the complex tasks. Thus, a model of performance on the Tower of Hanoi task (measured as the number of moves required to solve two specific Tower of Hanoi problems) based purely on the inhibition score was found to fit the data well – better than any other model based on a single construct and statistically no worse than a model based on all three constructs. From this, Miyake et al conclude that, at least for the version of the Tower of Hanoi used in their study, performance is a function of response inhibition but not of the other two control functions. Similar findings are reported for the other complex tasks.

Although the Miyake et al study has become a landmark, it has clear limitations stemming from the individual differences methodology and the statistical methods of confirmatory factor analysis and structural equation modeling. Consider first the analysis. In the second phase, good fits to the data in each of the five complex tasks are provided by several different models, each based on different combinations of the control constructs. While the authors provide some independent arguments for and against different models, choosing between them remains a subjective exercise. Of course the goodness of fit of these models depends crucially on the veracity of the first phase of the analysis, and even in the analysis of simple task behavior there is reason to doubt the specific isolation of the control functions. For example, the authors' analysis assumes that each of the nine simple tasks loads on one and only one of the three control functions. While the authors should be applauded for their use of confirmatory factor analysis (which, being hypothesis driven, is superior to standard factor analysis), it is not reported whether a three-factor model without this constraint does significantly better at accounting for the simple task data, or indeed whether a standard (unconstrained) factor analysis yields precisely three factors. A second critical limitation lies in the lack of any detailed account of how each function might contribute to performance on the individual tasks. What is missing are process accounts of the simple tasks which demonstrate that a single parameter expressed in each of, for example, the three response inhibition tasks, can account for the inter-task correlations, and moreover that this parameter is not implicated in process accounts of the other simple tasks.

Response Inhibition, Attentional Biasing and Monitoring

In fact, process models of many of the tasks considered by Miyake et al (2000) do exist. Such models can be seen as broadly supportive of a componential view of control functions, but they do not provide clear support for the specific functional decomposition hypothesized by Miyake et al. Consider response inhibition. A response inhibition account of Stroop would, presumably, involve a mechanism which inhibits the word-reading response when the task is to name the color, thus reducing interference between the two tasks/responses. This is not

how the commonly accepted model of the Stroop task, the interactive activation model of Cohen and Huston (1994; see also Cohen et al, 1990), functions. In this model Stroop interference arises from competition between two response pathways – a word-reading pathway which is highly practiced and hence strong, and a color-naming pathway which is less practiced and hence somewhat weaker. In order to generate a color-naming response it is necessary to selectively amplify the inputs to the color-naming pathway via task-demand units so that activation from that pathway can dominate activation from the word-reading pathway. This process is referred to as “attentional biasing”. If, however, the locus of interference effects within the model is attentional biasing, then the efficiency of this mechanism, rather than the efficiency of response inhibition, would appear to be a strong candidate for explaining individual differences in Stroop interference. (See Cooper & Davelaar, 2010, and Davelaar & Cooper, 2010, for further discussion.)

The Stroop task is of interest for a second reason. Behavioral studies of a range of tasks in which the dependent measure is response time (including the Stroop task) show that subjects adjust their performance across trials, with the simplest effect being the speeding-up of responses across successive correct trials and an immediate slowing of a response following an error – an effect known as the Rabbitt effect (Rabbitt, 1966). Such effects can be accommodated in computational accounts such as that of Cohen and Huston (1994) by assuming some kind of monitoring of performance combined with a mechanism for the on-line adjustment of attentional bias so as to optimize performance.

This approach was put forward by Botvinick et al (2001), who took three tasks where robust effects of on-line control had been demonstrated. The first was the Stroop task. Tzelgov et al (1992) found that Stroop interference is greater when congruent trials are common than when incongruent trials are common. The second was the Eriksen flankers task (Eriksen & Eriksen, 1974), where the subject must respond to a stimulus that is “flanked” on the left and right by distracters. Trials may be compatible (if the distracters are associated with the same response as the stimulus) or incompatible (if the distracters are associated with a different response to the stimulus). Subjects are faster on trials that are preceded by trials of the same type than trials that are preceded by trials of the opposite type (Gratton et al, 1992). The third was a simple choice response task known to produce a Rabbitt-like effect. In each case, Botvinick et al demonstrated that existing interactive activation models could account for the effects by a) introducing a conflict monitoring process that calculates the response conflict as the “energy” (Hopfield, 1982) of the output nodes, and b) using this energy term as a scalar value to modulate attentional bias in the first two cases and to prime responses in the third.

Neurophysiological evidence supporting the conflict monitoring hypothesis has been provided by a number of ERP and fMRI studies which link the process to a region of the medial frontal cortex, namely the anterior cingulate (see Botvinick, Cohen & Carter, 2004, for a review). However, both the process and the interpretation of anterior cingulate activation remain a matter of contention (see Stürmer, Sommer & Frensch, 2009). In particular, some have argued for a more general concept of monitoring, where what is monitored is not just response conflict, but also whether current actions are achieving higher-level goals (e.g., Krigolson & Holroyd, 2007).

Task Switching and Task Setting

A second set of cognitive control functions, typically considered independently from those associated with response inhibition and performance monitoring, relate to setting the current task or goal. Several studies in the 1990s found that when subjects were required to switch

from one simple stimulus-response task to another there was a cost associated with the task switch reflected in both a slowing of response and an increase in the likelihood of error. This time cost was not eliminated when subjects were primed for a forthcoming switch (see, e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995).

In a typical task switching experiment subjects are provided on each trial with two stimuli (e.g., a letter and a number presented on a video monitor) and one cue (e.g., the color of the background, which might be red or blue), and required to respond to one stimulus under one cue condition (e.g., categorize the number as odd or even if the background is red) and the other stimulus under the other cue condition (e.g., categorize the letter as a consonant or a vowel if the background is blue). The cue (and hence the required task) may change from one trial to the next (*switch trials*) or stay the same (*non-switch trials*). Almost inevitably in task switch experiments there is some degree of competition on any trial between responses from the two tasks, since stimuli relevant to both tasks are present simultaneously. While this may suggest a role for response inhibition in task switching experiments (and hence for individual differences in response inhibition to underlie individual differences in task switch costs), empirical results strongly imply that there is a component of the switch cost that is independent of response inhibition. For example, in the study of Miyake et al (2000) described above all correlations between individual scores on response inhibition tasks and task switching tasks were non-significant, despite significant correlations between scores on the different response inhibition tasks and between scores on the various task switching tasks.

Do switch costs reflect the operation of an identifiable cognitive control process? Rogers and Monsell (1995) argue that they do. They suggest that a process of task-set reconfiguration is required on switch trials but not non-switch trials (see also Rubinstein et al., 1991). This process assumes that, when performing a particular task, the cognitive system is configured with the appropriate set of stimulus-response associations. Task switching then requires that these associations be “swapped out” and replaced by those associations appropriate for the new task. Allport et al (1994) provide an alternative account. They argue instead that switch costs arise from what they term *task-set inertia* – between-task interference due to carry-over from the previous task. Stimulus-response associations for the new task on a switch trial must be activated so as to over-ride those of the previous task, but on the Allport account this activation of task-set occurs on all trials (both switch trials and non-switch trials).

Two computational accounts of task-switching support the task-set inertia view. Gilbert and Shallice (2002) extended the model of Cohen and Huston (1994) to account for task-switching effects in the Stroop task. Such effects occur when, with Stroop-like stimuli, the task switches between naming the word on some trials and naming the ink color on other trials. Gilbert and Shallice assumed that a portion of activation of the task demand units of the Cohen and Huston model persists across trials. On any trial this persistent activation is combined with top-down input for that trial which indicates whether the task should be color naming or word reading. On switch trials the persistent activation conflicts with the top-down input, resulting in weaker attentional biasing and hence slower responses and more errors. On non-switch trials the persistent activation is consistent with the top-down input, resulting in stronger attentional biasing and hence faster responses and fewer errors. Using this model, Gilbert and Shallice were able to simulate effects of task-switch and task-non-switch on successive trials of the Stroop task.

Curiously, the same mechanism (attentional bias) is used in effectively the same model (Cohen and Huston’s Stroop model) by Gilbert and Shallice (2002) to capture task-switch

effects and by Botvinick et al (2001) to modulate performance in situations of high response conflict. This suggests a common computational-level explanation of task-switching and response conflict phenomena, namely that the key control process operating in both cases is attentional biasing. As noted above, however, individual difference evidence suggests that task-switching and response inhibition are distinct control processes, so there is clearly more to the story than these simulations might suggest.

A second computational account which effectively elaborates on the task-set inertia account of switch costs is provided by Altmann and Gray (2008). Their analysis of task-switching starts from a functional perspective. It is argued that task-set is represented in episodic memory but that this representation must decay given the biological substrate of memory and the requirement that we be able to switch tasks at all. In addition it is argued that given this decay it is necessary, in situations which require maintenance of task-oriented performance over an extended time interval, to frequently or repeatedly reactivate the episodic memory representation of the current task set to ensure that it remains sufficiently active to control current behavior. The resultant model has much in common with the Gilbert and Shallice (2002) model, though it is framed in a more general account of task-set memory and shown to account for a range of effects beyond those addressed by Gilbert and Shallice.

If, as these two models suggest, switch costs are due to task-set inertia (or to twin processes of task-set activation and decay as in the Altmann and Gray model) and not a process of task-set reconfiguration, then the relevant cognitive control processes are better identified as task *setting* (rather than task *switching* or task *shifting*) processes. Moreover if the Altmann and Gray (2008) position is correct, then task setting reflects two distinct control processes – *task-set repetition priming*, which is cognitive and strategic, and *task-set decay*, which is biological and automatic. Both of these control processes are functional. Individual differences in performance on switching tasks such as those found by Miyake et al (2000) then presumably correspond to individual differences in one or both of these processes.

There is one further account of the processes underlying task-switching which requires special attention. Logan and Gordon (2001) consider how models of putatively separable cognitive subsystems might be related to each other. They focus on two specific models: Bundesen's Theory of Visual Attention (TVA; Bundesen, 1990) and Nosofsky and Palmeri's Exemplar-Based Random Walk model of classification (EBRW; Nosofsky & Palmeri, 1997). Each model is parameterized, and different parameter settings are required when the models are applied to different tasks. Logan and Gordon demonstrate how the models may be combined so as to apply to a simple dual-task situation. A critical aspect of this application is that the models require different parameter settings for different task combinations. Thus, Logan and Gordon further present an account of cognitive control in which one role of the controller (the so-called "central executive") is to set appropriate values of the parameter within TVA and EBRW. Thus, on this account, a component of the switch cost relates to the setting of parameters within subsystems. This parameter setting would seem to be a candidate cognitive control function.

Working Memory Monitoring, Maintenance, Updating and Gating

Altmann and Gray's model makes a clear link between task setting and an episodic memory control process. On the basis of this, one might attempt to subsume memory control processes under a single control component. However, Miyake et al's analysis suggests that control processes related to working memory are at least partially independent from those involved in task setting.

The critical element of the process referred to by Miyake et al (2000) as memory monitoring/updating is the manipulation (rather than simply maintenance) of information in working memory. Evidence for this as a distinct control function comes from strong intercorrelations in performance between three tasks that appear to require such manipulation. Thus Miyake et al found that performance on the “keep track task”, in which subjects were presented with a list of nouns of different categories (e.g., names of animals, colors, countries, etc.) and required to keep track of the last instance of each category, correlated strongly with performance on the “letter monitoring task”, in which subjects were presented with a letter sequence and required at random points to recall the last four letters. Here again is an area where process models that clarify possible mechanisms involved in the manipulation of the contents of working memory, or more generally in “memory monitoring/updating”, are essential if we are to go beyond Miyake et al’s correlational evidence and understand the putative common mechanisms behind these tasks. Such models might provide insight into, for example, whether memory monitoring and memory updating are distinct processes, whether they are better characterized as a unitary process, or indeed whether either can be further decomposed.

While models of Miyake et al’s tasks are yet to be developed, O’Reilly and Frank (2006) have published a neurally-inspired model of a task that is specifically designed to tax working memory control processes – the so-called 1-2-AX task. In this task subjects are presented with a sequence of stimuli and required to indicate when a target sub-sequence occurs. The target subsequence changes throughout the task. When a “1” occurs in the stimulus stream the target sequence is an “A” followed immediately by an “X”. When a “2” occurs it is a “B” followed immediately by a “Y”. Successful performance of the task requires monitoring of the input, rapid encoding when the current input indicates a change of target or is potentially the first element of the target sequence, and monitoring of working memory to detect whether the current input is the second element of the target sequence. The key insight embodied in the model is that working memory is held to operate in one of two modes: *active maintenance* (as required when maintaining the current rule) or *selective updating* (as required when encoding the current stimulus). Working memory is conceptualized as a set of slots, and switching between modes is operationalized through a gating process which applies to individual slots. When a slot’s gate is open perceptual input updates the contents of that slot. When it is closed the current contents of the slot are actively maintained. Gating of working memory slots (rather than maintenance or updating) is therefore the critical control function within the O’Reilly and Frank model.

The simulation results of O’Reilly and Frank demonstrate that gating is adequate as a control process for the 1-2-AX task. It would seem also adequate (when extended with mechanisms for semantic categorization that will draw on long term or semantic memory) for Miyake et al’s keep track task. Miyake et al’s letter monitoring task, however, would appear to require more complex control mechanisms to handle the explicit manipulation or temporal tagging of working memory contents in order to maintain sequential order information related to each item.

Architectural Approaches

The now-standard model of working memory (e.g., Baddeley, 2000) conceptualizes the working memory system as two content-specific slave subsystems (the phonological loop and the visuospatial sketchpad) operating under the control of a central executive. Manipulation of the contents of working memory is one of four functions considered by Baddeley (1996) to

be performed by this central executive. The other three concern the coordination of multiple concurrent tasks, the switching of retrieval strategies as a function of task demand, and the ability to selectively attend to a stimulus. Baddeley does not suggest that these processes represent a complete partitioning of the functions of the central executive, and while he also does not provide a box and arrow diagram showing the inter-relations between these putative processes, his framing of the problem of decomposing the central executive makes clear the need to relate control processes to each other and to the cognitive architecture as a whole.

An earlier architectural approach, that of Norman and Shallice (1986), was in some ways more explicit. Norman and Shallice argued that behavior is the product of a simple system capable of performing routine tasks – contention scheduling – that is modulated in non-routine situations or situations demanding particular care or attention by a second system – the supervisory attentional system. Contention scheduling was held to consist of behavioral schemas which competed to effect behaviors through activation-based processes. The inner details of the supervisory system were not initially described, but its interface with contention scheduling, through the top-down excitation or inhibition of schemas, was. This top-down excitation of schemas corresponds closely to the putative control function of attentional biasing described above. Moreover, an important feature of the Norman and Shallice framework is that it provides an answer to a question which we have so far ignored, namely, how might we more rigorously define control – or perhaps more properly in this context “executive” – functions. One answer is that they are the functions of the supervisory attentional system.

The internal functioning of the supervisory attentional system was fleshed out to some extent by Shallice and Burgess (1996), who associated eight distinct processes with the system. Several of these processes map more or less onto control functions identified above, such as goal setting, monitoring, and episodic memory retrieval, but this initial decomposition was relatively coarse. More recently a series of papers by Shallice, Stuss and colleagues have sought to fractionate or decompose the supervisory attentional system using data from studies in which groups of neurological patients with focal, frontal, brain injuries complete a battery of tasks (e.g. Alexander et al, 2005, 2007, Picton et al, 2007; Stuss et al, 2000, 2001, 2005). Thus, Shallice et al (2008a, 2008b) provide an elaboration of the control processes of the supervisory attentional system in relation to a specific task – one from the task-switching paradigm – and, through a series of primarily behavioral patient studies, relate those processes to specific regions of the prefrontal cortex.

The model posits four control functions. Two of these, task-setting and monitoring, have already been discussed. They are held to be operationalized within the left lateral and right lateral prefrontal cortex (PFC) respectively. For example, Shallice et al (2008a) found that patients with left lateral PFC lesions produced more errors on the earlier trials of a task-switching task than controls, but not on later trials. This (along with other similar evidence) is interpreted as indicating that left PFC patients are impaired in setting the current task. Once the task is set, however, left lateral patients perform as well as controls. Patients with right lateral PFC lesions, on the other hand, show deficits in tasks which involve avoiding capture errors or judging the passage of time – tasks where success requires monitoring of performance.

The remaining two control functions are *energization* and *attentiveness*. These are novel to the approach. Stuss et al (2005) report that patients with lesions to superior medial PFC (which they take to include anterior cingulate cortex – the region held by Botvinick et al

(2004) to be responsible for conflict monitoring) tend to produce slow responses across a wide range of reaction-time tasks. This, it is suggested, reflects a deficit in accumulating activation sufficient for a response – the process they refer to as energization (see also Alexander et al, 2005). Patients with inferior medial lesions, by contrast, show high error rates on switch trials (Shallice et al, 2008a). They are also prone to the production of so-called “set-loss” errors in tasks that require maintenance of a rule or “mental set” (Stuss et al, 2000). These effects are interpreted as arising from a deficit in sustaining attention on a task, that is attentiveness.

One hurdle that this approach needs to overcome is the computational operationalization of the key constructs of task-setting, monitoring, energization and attentiveness. Simulation work here would seem to be critical in demonstrating that the account is indeed consistent with the observed empirical effects. These effects include, in some cases, null effects which are held to result from factors which may work in opposition such as learning and attentiveness.

Cognitive Control as Componential: A Summary

To summarize, while there is considerable debate in the literature reviewed above, there is also something of a consensus that control functions are componential. That is, we may study response inhibition or task setting or other putative control functions as if they are separable processes. If this is the case, then one might expect the emergence of a catalog of a small set of well-defined control functions. Such a catalog is yet to develop. In fact there is little agreement on the functions themselves, leading to something of a menagerie of putative control functions. This menagerie includes, minimally: response inhibition, attentional bias, performance monitoring, conflict monitoring, response priming, task setting, task switching, and the setting of subsystem parameters, as well as working memory control functions such as monitoring, maintenance, updating and gating. In addition there are the multiple functions of the Baddeley’s central executive and Shallice’s supervisory attentional system.

Yet there are other putative control processes which have not as yet been touched upon. Thus, it is frequently assumed, in addition to response inhibition, that there are more general processes of cognitive inhibition. For example, Harnishfeger and Pope (1996) argue that improvements in children’s memory performance with age are due to the increasing efficiency of cognitive inhibition in suppressing unwanted or irrelevant information, while Houdé et al (2000) argue from functional MRI evidence that it is possible, with training, to inhibit perceptual processes. While there remains some dispute over the nature (and even existence) of cognitive inhibition (see Gorfein & MacLeod, 2007), the construct has been widely adopted within communities studying pathologies such as schizophrenia (e.g. Beech et al, 1989) and obsessive-compulsive disorder (Chamberlain et al, 2005).

Furthermore in the study of Miyake et al (2000) it was found that individual differences in dual-tasking (defined as a performance decrement occurring when two tasks are performed concurrently, controlling for performance on the individual tasks when performed in isolation) did not correlate with any of the three factors explored in the nine simple tasks. Miyake et al took this to suggest that there are control processes associated with dual-tasking that are above and beyond response inhibition, task shifting and memory updating/monitoring (see also Logie et al, 2004). A subsequent study by Friedman and Miyake (2004) using the same methodology but different tasks found a dissociation between response inhibition and what they term “resistance to proactive interference”. Conceivably the mechanisms that facilitate resistance to proactive interference may also facilitate dual-tasking.

Cognitive Control as Emergent

One could be forgiven, based on the foregoing discussion, for adopting a view of the cognitive system as including a set of special purpose mechanisms, with each dedicated to a specific aspect of cognitive control. Two related lines of computational work suggest that this would be premature. Much of the early empirical evidence for control processes was based on studies in which subjects were required to complete, more or less simultaneously, two choice reaction-time tasks. Typically task stimuli would be presented in different modalities (e.g., auditory and visual) with an interval of 500 ms or less between stimuli. The general finding – referred to as the Psychological Refractory Period (PRP) – was that when the inter-stimulus interval was very short the response to the first stimulus would be unaffected by the dual-task situation but the response to the second stimulus would be delayed. PRP effects might be attributed to processing “bottle-necks” (see Pashler, 1994, for a review), but Meyer and Kieras (1997a, 1997b) demonstrated through simulations with the EPIC (Executive Process Interactive Control) cognitive architecture that many such effects could be explained by adaptive scheduling strategies which were constrained by serial input and output channels. Thus, while EPIC includes basic operations for memory access and configuring motor responses, it does not appeal to control processes such as attentional biasing or response inhibition. Similar comments apply to the ACT-R architecture (Anderson et al, 2004), which incorporates EPIC’s serial input and output channels, but which has been applied to a much wider range of empirical phenomena. This includes the Stroop task (Lovett, 2005).

In Lovett’s ACT-R model of the Stroop task two “cognitive processes” (name the word and name the ink color) effectively compete on each trial. Each process is implemented as a production rule (i.e. a set of conditions and a set of actions), and each production rule has a learned “utility”. The probability of a production firing is determined by its utility compared to that of its competitors (where two or more productions will compete on any processing cycle if each production’s conditions are satisfied). Word naming (i.e., reading) is assumed to have greater utility than color naming, so the model will, other things being equal, be more likely to read a word than name its ink color. Utilities are dynamically adjusted – they are increased if the production ultimately succeeds in achieving the current goal and decreased otherwise. Regardless of which production rule fires on any trial, it is also necessary to retrieve color-name or word-name information from declarative/semantic memory. The time taken by this retrieval process depends on the activation level of the to-be-retrieved information, and it is assumed that, all other things being equal, word-name activation is greater than color-name activation. Equally, however, activation is temporarily boosted when information is retrieved, so if an item is recalled twice in relatively quick succession the second recall attempt will proceed more quickly than the first. Three factors therefore interact in the Lovett (2005) model: production utility, production utility learning, and semantic memory retrieval. With these three factors, Lovett is able to account for a range of Stroop effects, including those discussed by Botvinick et al (2001) in relation to trial-type frequency and response conflict. Critically, however, these three factors are present in all ACT-R models – they are not special purpose control functions that come in to play in non-routine situations. Rather, they are ubiquitous hard-wired architectural mechanisms. Consequently it may be argued from an ACT-R perspective that phenomena typically associated with special purpose cognitive control functions are effectively epiphenomenal.

The Current Topic: Perspectives on Cognitive Control

The above discussion has focused on behavioral and computational approaches to understanding cognitive control. Clearly there are many unresolved questions beyond those

highlighted in this introduction. It is the purpose of this collection of papers to stimulate debate by bringing the different perspectives offered by the cognitive sciences to bear on these questions. Thus, in addition to this introduction, this Topic consists of five target articles that present different perspectives on cognitive control and its relevance across the cognitive sciences. Integrative commentaries on those articles and author replies will be published in a subsequent issue.

Each of the target articles presents a potentially controversial position. **Stout** argues that comparative evidence from primate evolution and the archeological record supports, at a gross level, a distinction between the control functions of lateral and ventromedial prefrontal cortices, with the former associated with sensorimotor integration and the latter associated with self regulation. **Cragg and Nation** approach the issues from a developmental perspective with a particular focus on the role of inner speech in cognitive control. They argue that inner speech facilitates cognitive flexibility (and specifically task shifting) by supporting the activation of relevant task sets. **Mandik's** contribution focuses on philosophical aspects of cognitive control, relating control to consciousness. He takes issue with views of consciousness based purely on sensory information, and argues instead that what he terms *control consciousness* is dependent upon states of activity in the motor hierarchy. In making his argument, Mandik draws upon control theory and the idea prevalent in the motor control literature (e.g., Wolpert & Ghahramani, 2000) that such control involves so-called forward models (which predict the consequences of an action and which can therefore be used by sensory and motor systems to create expectations and therefore anticipate feedback) and inverse models (which, given the current state of the motor system and a desired outcome, predict the action required to produce that outcome). This idea is picked up in the contribution of **Alexander and Brown**, who survey computational neuroscience approaches to attentional biasing, task switching and performance monitoring. They then present a novel synthesis based on the possibility that medial prefrontal cortex implements similar forward and inverse models, and uses the resulting predictions and error feedback to modulate (and hence control) cognitive processing. The final target contribution, from **Lenartowicz, Kalar, Congdon and Poldrack**, squarely addresses the componential/emergent question using a novel approach to the analysis of brain imaging data. These authors present a case for an ontology of cognitive control functions. They suggest that if a control function has some kind of reality at the neural level (and so is more than just a construct), then it “should be associated with a distinct [...] pattern of neural activity”. It is demonstrated through a meta-analysis that the putative control function of response selection has this property, but that current evidence for the distinction at the neural level between response inhibition, working memory and cognitive control more generally is weak. While the coverage of these articles is broad, it is not exhaustive. For example, none of the target articles address the perspective on cognitive control offered by current developments in cognitive robotics. Some of these omissions will be addressed in the commentaries to be published in a subsequent issue of *TopiCS*.

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