

Task Switching

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Introduction

Task switching is widely considered to be at the nexus of executive control in the human cognitive system. The ability to switch tasks is thought to require extensive high-level cognitive processing, ranging from instantiating abstract representations to preparing task-specific processes and monitoring response selection and execution. The behavioral outcome of this processing is a robust switch cost – slower and more error-prone performance when switching tasks than when repeating tasks.

Switch costs are frequently interpreted as reflecting the duration of time-consuming executive control processes that reconfigure the cognitive system when switching tasks, although this idea is debated in the behavioral literature on task switching. Some researchers have questioned whether switch costs are valid indices of executive control processes, whereas others have challenged the very notion that task switching involves executive control. There is abundant evidence indicating that basic psychological processes subserving attention, memory, and perception contribute to switch costs, compromising the interpretation of many behavioral effects as diagnostic evidence of executive control. Given that the cognitive architecture underlying switch costs and related effects is a matter of debate, it is important to exercise caution when interpreting proposed linkages between neural activity and specific cognitive processes putatively involved in task-switching performance.

With or without full appreciation of this point, many researchers have begun to explore the neural correlates of task switching. An increasing focus on identifying the neural substrates of various components of task-switching performance has produced a wealth of knowledge about task representation, selection, preparation, and switching. However, the quest to identify switch-specific neural mechanisms has proven to be challenging, with mounting evidence indicating that a distributed frontoparietal cortical network underlies task-switching performance.

Task Representation

To perform a task, it is necessary to have access to a representation of the associations between relevant stimuli and responses (i.e., task or stimulus–response

mapping rules). A task representation can be considered part of a broader configuration of the cognitive system known as a task set, which includes task-specific processes that act on these representations. Many researchers propose that switching tasks requires reconfiguring the existing task set, in part to instantiate different task rules.

A brain area that is strongly implicated in task representation is prefrontal cortex (PFC). It has been proposed that PFC is involved in the acquisition, representation, and maintenance of abstract task rules for goal-directed behavior. These task rules are assumed to be extracted from past experience, in part through myriad connections to and from sensory and motor areas throughout the brain. The strongest evidence that PFC encodes task rules comes from single-cell recordings in monkeys performing different tasks. When monkeys are cued to adopt a specific task rule for responding to a stimulus, a substantial proportion of single neurons in PFC have been found to fire selectively for a given task rule. These neurons were considered rule selective because they fired after cue onset or during the delay period following the cue, regardless of the specific cue used to signal the task rule. Moreover, monkeys were able to generalize the rule to new, unseen stimuli. Such rule-selective neurons have been identified throughout dorsolateral, ventrolateral, and orbital PFC.

Task rule-selective neurons have also been found in parietal cortex. There is evidence that single neurons in the lateral bank of the intraparietal sulcus (IPS) and on the angular gyrus may encode task rules. These neurons had markedly increased firing approximately 400 ms after cue onset and fired regardless of the perceptual cues associated with each rule, suggesting that abstract task information (rather than the sensory features of the cues) had been encoded.

The evidence implicating prefrontal and parietal cortices in task representation suggests that these brain areas should be active when switching tasks, based on the proposal that task switching involves changing the existing task representation or task set. This suggestion is supported by several studies on task selection, preparation, and switching.

Task Selection, Preparation, and Switching

The primary goal in many task-switching situations is the selection and performance of a relevant task in the face of irrelevant, competing tasks. Task selection becomes crucial when stimuli are multivalent (i.e., associated with more than one task), creating

ambiguity about which task to perform. Such ambiguity can be resolved by presenting a task cue prior to or in conjunction with the imperative stimulus, enabling researchers to investigate the neural underpinnings of how tasks are selected, prepared, or switched in advance or during task execution.

Much of our knowledge concerning task switching has come from studies involving event-related functional magnetic resonance imaging (fMRI), in which researchers measure changes in the blood oxygen level-dependent (BOLD) signal elicited by different types of trials. The basic analytical strategy has been to contrast task switches with task repetitions (or other baselines) to determine which brain areas are more 'active' (i.e., generate stronger BOLD signals) when switching tasks. Although there are potential problems with this strategy (discussed later), it has yielded a large body of knowledge about the neural basis of task switching.

Neural Correlates of Task Switching

As with task representation, there is evidence that PFC underlies task selection, preparation, and switching. There is a general consensus that PFC is involved in various activities related to executive control, such as selective attention, task management, goal maintenance, and the regulation of on-line processing involving the contents of working memory. Evidence suggesting that PFC is involved in goal maintenance in dual-task and task-switching situations has come from several fMRI studies. For example, dual-task performance that involves keeping a single goal in mind activates dorsolateral PFC (Brodmann area (BA) 9), whereas keeping a primary goal in mind while performing concurrent subgoals tends to activate dorsal frontopolar PFC (BA 10). Some researchers have proposed that goal activation in PFC may bias or configure processing in other brain areas to enable implementation of the relevant task set, implying top-down control over task processing. Direct evidence in support of this proposal comes from single-cell recordings in split-brain monkeys performing a cue-stimulus association task; activity in inferior temporal cortex related to task processing was found to be modulated by activity in PFC.

The notion that PFC is involved in selecting and maintaining goals in preparation for performing or switching tasks is the main conclusion from many studies. Bilateral dorsolateral PFC (BA 9/46) activation has been observed following different types of task cues in task switching, suggesting that cue-based selection of task goals is subserved by PFC. Evidence indicates that a similar type of cue-elicited task preparation may occur in an area at the junction of the inferior frontal sulcus and inferior precentral

sulcus – the so-called inferior frontal junction (which includes parts of BA 6, 8, and 44). Activation in the inferior frontal junction is separate from that associated with cue encoding and is thought to reflect task management or the updating of task representations in preparation for task switching. However, activity associated with task-switching performance extends to other regions of PFC, such as frontopolar, ventrolateral, and medial PFC.

Regarding the medial surface of the frontal lobes, researchers have also focused on the role of anterior cingulate cortex (ACC; BA 24/32) in task-switching performance. ACC is thought to play an important role in resolving conflict situations and monitoring for errors; therefore, it is likely involved in task selection when stimuli are multivalent and there is a chance of performing the wrong task. In dual-task performance, ACC activation has been interpreted as reflecting response selection among competing alternatives. In task-switching performance, ACC activation has been observed when switching between Stroop color-word tasks, which are thought to require executive control processes to resolve stimulus-induced conflict (e.g., the word 'green' printed in the color red). Even in non-Stroop task-switching situations, ACC is sometimes active and tends to be accompanied by activity in dorsolateral PFC, especially when tasks occur unpredictably and stimulus onset is uncertain. This latter point has received some attention in studies on the effects of manipulating task predictability, either by contrasting fixed and randomized task orders or by comparing cues that either specify the upcoming task or only indicate whether to switch or repeat tasks. These studies have led to the emerging idea that PFC is organized along an anterior-posterior axis, with activation becoming more anterior as task performance requires more endogenous (i.e., internal) control.

Another anterior-posterior axis figures prominently in neuroimaging research on task switching, although this axis extends across the brain from prefrontal to parietal cortex. Consistent with some of the studies on task representation, there is evidence that areas of parietal cortex are highly active when switching tasks. One such area is the IPS (BA 39/40), which has been found to be more active for task-switching than dual-task performance. The IPS is more active when task order is unpredictable rather than predictable, although there is also evidence of its involvement in cue-elicited task preparation. Moreover, there is emerging evidence for possible functional dissociations in parietal cortex, with posterior areas being more active when switching between task-relevant dimensions, and anterior areas being more active when switching between stimulus-response mapping rules.

These activations in parietal cortex tend to be interpreted in relation to activations in PFC. As mentioned previously, PFC is thought to provide top-down control signals for coordinating neural activity in other brain areas. Some researchers have interpreted activation in PFC as reflecting the selection of task-relevant neural pathways or instantiation of the appropriate task representation, with concurrent activation in parietal cortex reflecting the organization or implementation of task-specific stimulus-response mapping rules. In other words, PFC is viewed as the source of preparatory signals for biasing activation in parietal cortex and other brain areas.

Although much of the neuroimaging literature tends to emphasize the involvement of the frontal and parietal cortices in task-switching performance, many other brain areas have been found to be more active when switching than when repeating tasks, such as the cerebellum and various regions in the temporal and occipital cortices. The consistency of these activations across studies is unclear, and functional interpretations of their roles in task switching are lacking, in part because researchers have been more captivated by the frontal and parietal cortices. An important avenue for future research on task switching will be to delve into these relatively unexplored brain areas to determine if and how they contribute to the broader network of neural activity underlying task-switching performance.

Rule Switching

Given that task switching is often thought to require changing task (or stimulus-response mapping) rules, it is useful to search for neural correlates of rule switching in related experimental paradigms. One such paradigm is the Wisconsin Card Sort Test (WCST), which was a precursor to some of the modern research on task switching. In the WCST, subjects are given a set of cards on which stimuli of varying number, color, and shape are printed. The task is to learn to sort the cards into piles related to a specific stimulus dimension (e.g., color), based on feedback from the experimenter. After many consecutive correct responses (indicating that the sorting rule has been learned), the relevant stimulus dimension is surreptitiously changed, and subjects have to discover the new sorting rule (e.g., shape). The process of adopting a new sorting rule is thought to require changing the existing task set; hence, the neural correlates of WCST performance should be similar to the neural correlates of task-switching performance.

There is abundant evidence implicating PFC in WCST performance. Early neuropsychological studies revealed that patients with lesions of dorsolateral PFC performed worse than control subjects. fMRI

studies have examined different components of WCST performance within PFC. Activation of the posterior part of the bilateral inferior frontal sulci (BA 45/44) increases as the number of relevant sorting dimensions increases. The right anterodorsal part (BA 46) and bilateral posteroventral parts (BA 8/44) of PFC tend to be more active when a change in the task rule requires shifting attentional set (e.g., to a different stimulus dimension), but only the latter areas are activated when the task rule is merely reversed. Although these findings of bilateral activation in PFC indicate that both cerebral hemispheres are involved in WCST performance, evidence suggests that there is functional specialization, with regions of right lateral PFC activated in response to negative feedback (when the sorting rule changes) and regions of left lateral PFC activated when updating the existing task set. Collectively, these findings of PFC activation, as well as reports of parietal cortex activation, are consistent with the neuroimaging results of many task-switching studies, suggesting that the brain areas involved in WCST performance may overlap with those involved in task-switching performance. Indeed, this suggestion is supported by a meta-analysis of WCST and task-switching studies that revealed a common pattern of distributed frontoparietal cortex activation across these paradigms.

Task-Set Inhibition

The preceding review may convey the misconception that task switching is only about the activation of task representations or stimulus-response mapping rules, but it is important to consider some of the neuroimaging evidence for inhibition in task-switching performance. When switching between different tasks (denoted A, B, and C) across a series of trials, performance is slower on the third trial of an ABA task sequence than a CBA task sequence. This impairment in performance of a recently abandoned task has been attributed to task-set inhibition – the inhibition of a previously relevant (but now irrelevant) task set when performing a different task.

Studies have found evidence suggesting that task-set inhibition involves right PFC, consistent with findings associated with other types of inhibition. Contrasting ABA and CBA task sequences in fMRI work has revealed activation in right lateral PFC (BA 45, 9/46) as well as left inferior temporal cortex (BA 37) and occipital cortex (BA 19). However, these results have been interpreted as reflecting increased task-set engagement in response to inhibition rather than task-set inhibition *per se*. Further evidence for the involvement of right PFC in task-set inhibition comes from the finding that patients with focal lesions of right PFC exhibit no behavioral manifestation of

task-set inhibition, unlike patients with lesions of left PFC and control subjects.

Correlations between Neuroimaging and Behavioral Data

If the various inferences about the roles of different brain areas in task switching are valid, then it should be possible to identify correlations between activations in specific regions and behavioral measures of task-switching performance. A positive correlation has been observed between activation of the left inferior frontal junction (as well as the presupplementary motor area) and the magnitude of a behavioral cuing effect (i.e., the decrease in response time with an increased cue–target interval), which has been interpreted as evidence of cue-elicited task preparation. When switching between Stroop color–word tasks, activation of left dorsolateral PFC is strongest for those subjects who exhibit the weakest behavioral effects related to conflict, suggesting a role for this brain area in task preparation, whereas activation of ACC is strongest for those subjects who exhibit the strongest conflict effects, suggesting a role for ACC in performance monitoring. A finding that is related to the aforementioned results concerns a region encompassing parts of the presupplementary motor area and ACC: as activity in this region increases, switch cost increases. This finding has been interpreted as evidence of neural activity increasing in parallel with the degree of interference at the time of task performance, consistent with the observation of increased switch costs with increased activity in task-irrelevant brain areas. However, there have been some reported failures to observe correlations between switch cost and neural activity, which may reflect the fact that multiple brain areas contribute to task-switching performance, a point discussed later.

Switch Specificity

Research on task representation, selection, preparation, and switching implicates an extensive frontoparietal cortical network and many other brain areas in task-switching performance. This distributed neural basis for task switching raises an important question that has motivated many neuroimaging studies: are there any brain areas that are specific to switching tasks? This multifaceted question can be approached from three angles: analytical, empirical, and conceptual.

The Analytical Angle

Identifying a switch-specific brain area in neuroimaging research usually requires contrasting task switch trials with appropriate baseline trials. A common

baseline used in fMRI studies is the pattern of activation on task repetition trials, resulting in a task switch–task repetition contrast. When a specific brain area is reliably more active (i.e., generates a stronger BOLD signal) when switching tasks than when repeating tasks, this contrast will tend to be significant. Although some researchers have used this contrast to identify brain areas involved in task switching, an important point that is sometimes overlooked is that the contrast indexes relative, not absolute, activation across different types of trials. In other words, a specific brain area may be active on both task switch and task repetition trials but exhibit stronger activation on task switch trials, yielding a significant contrast. It is clearly inappropriate in this situation to claim that the brain area associated with the contrast is switch specific (i.e., it is only involved in switching tasks), and this problem extends to region-of-interest analyses that are based on the pattern of activation associated with task repetition trials.

This issue can be partially addressed through the use of multiple baselines. For example, some researchers have supplemented the task switch–task repetition contrast with a task repetition–fixation contrast in an effort to separate out those brain areas that are active on task repetition trials. There are two potential problems with this strategy. First, the processing required for nontask events such as fixation may differ substantially from that required for task repetition trials, obfuscating the interpretation of any brain areas that yield significant task repetition–fixation contrasts. Second, application of this strategy requires making the assumption that task switch trials not only include switch-specific processes but also all of the processes engaged on task repetition trials, which may not necessarily be the case. This second problem also applies to the use of other tasks (e.g., Stroop color–word tasks) and situations (e.g., dual-task performance) as comparison conditions for task switch trials. Although these tasks and situations may be comparable to task switching (in that they are thought to require executive control processing), the differences between complex tasks may complicate any inferences regarding switch-specific brain areas.

The Empirical Angle

Analytical issues aside, there is little empirical evidence of switch-specific brain areas. Through the use of multiple baselines, some researchers have found that the same brain areas are active on both task switch and task repetition trials, suggesting that task-switching performance is not restricted to a single brain area and that there is no brain area specifically

involved in task switching. This suggestion is supported by contrasts of task-switching performance with other situations (e.g., dual-task performance), which have revealed activation of a common bilateral prefrontoparietal cortical network. Similar findings have emerged from integrative meta-analyses of Stroop and task-switching performance and different types of attention shifting (which included task switching and rule switching). For example, meta-analyses of attention-shifting studies have revealed substantial activation overlap in areas such as medial PFC, medial, superior, and inferior parietal cortex, and premotor cortex (as well as bilateral dorsolateral PFC and bilateral anterior insula, but to a lesser extent); these results have been interpreted as evidence that different types of attention shifting all depend on a similar set of working memory and executive control processes.

Some researchers have argued against the notion of switch-specific brain areas on the basis of other evidence. For example, the lack of a relationship between switch-related neural activity and behavioral measures of task-switching performance has been interpreted as evidence against a switch-specific neural mechanism. An electrophysiological study of changes in the electrical brain potential over frontal cortex, supplemented with fMRI data, did not yield any clear markers of task-switching performance. On a related note, there is evidence that changes in event-related electrical brain potentials following a single task switch trial can persist over a subsequent run of task repetition trials, suggesting that activity on task repetition trials may not be pure (in the sense of not reflecting task switching). A direct implication for fMRI studies of task switching – which typically involve measuring changes in cerebral blood flow over several seconds – is that task repetition trials may not represent an appropriate baseline for task switch trials in standard contrasts.

The Conceptual Angle

The lack of evidence for switch specificity is not surprising if one considers the broader conceptual issue of what is likely involved in task switching. In the behavioral literature, many component processes have been proposed to account for task-switching performance, and it is unlikely that all of these processes are exclusive to task switching or implemented in the same brain area. The idea that task switching requires the integration of various perceptual, attentional, mnemonic, and motor processes is supported by the abundant evidence implicating an extensive frontoparietal cortical network in task-switching performance and the conjecture that frontal areas

integrate and coordinate information that is then transmitted to parietal areas for task-specific processing. For these reasons, it may be difficult to find robust correlations between switch cost and neural activity, and the search for switch-specific brain areas may be in vain. Indeed, some authors have argued that attempts to localize any complex cognitive processes in the brain may be misguided because such processes likely involve a distributed, interacting network of brain areas. If this is the case, then perhaps cognitive neuroscientists should focus their efforts on identifying and understanding the functional linkages between different brain areas involved in task-switching performance rather than seeking evidence of switch-specific neural mechanisms.

Conclusion

Despite the fact that the cognitive neuroscience of task switching is only approximately 7 years old, much progress has been made toward identifying the neural correlates of task-switching performance. Research on task representation, selection, preparation, and switching suggests that myriad brain areas – stretching from prefrontal to posterior parietal cortices – are involved in task switching. Although there has been interest in isolating switch-specific neural mechanisms, careful consideration from analytical, empirical, and conceptual angles suggests that no single brain area underlies performance. As researchers continue to delve into the multifaceted nature of task switching, a clearer picture of the intricate functional connections between brain areas will likely emerge, hopefully providing insight into the cognitive architecture of task switching and a window to the broader realm of executive control in human cognition.

See also: Attentional Networks in the Parietal Cortex; Cognition: An Overview of Neuroimaging Techniques; Executive Function and Higher-Order Cognition: Neuroimaging; Parietal Cortex and Spatial Attention; Prefrontal Cortex: Structure and Anatomy; Prefrontal Cortex.

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