Executive Control, Willed Actions, and Nonconscious Processing

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Abstract: Neuroimaging studies have identified a number of cortical areas involved in the executive control of conscious actions. The areas most frequently implicated are prefrontal and cingulate cortices. Evidence suggests that both of these areas may be essential for executive control of willed action. Prefrontal cortex, however, may be responsible for the initial processing. Executive control is usually discussed with reference to willed actions and is assumed to regulate complex cognitive responses. Although many implicit processes involve complex responses, it is not known whether these actions are also controlled by executive processes. Significantly, some implicit tasks like those involving motor sequence learning and cross-modality priming activate the same areas of prefrontal cortex that are implicated in the executive control of willed actions. It is, however, not clear whether a single executive process controls both implicit and explicit processes, or the implicit processes are regulated by a separate set of executive control having distinct neuroanatomical location and processing properties. *Hum. Brain Mapping 9:38–41, 2000.*
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Key words: implicit memory; working memory; explicit memory; prefrontal cortex; cingulate cortex

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INTRODUCTION

Cognitive and neuroimaging studies have identified three dissociable components of working memory: storage, rehearsal, and central executive [for review see Baddeley, 1996; Smith and Jonides, 1999]. Although several stimulus specific areas have been implicated in the storage and rehearsal, there is disagreement about precise location and nature of some aspects of the central executive, which is primarily responsible for attentional control of working memory. Clark and colleagues [1999] have studied updating process, which is a function of the central executive.

The concept of central executive has been developed on a model of the control of action proposed by Norman and Shallice [1986]. According to this model, willed and automatic actions are controlled at different levels depending on the degree of task difficulty and complexity. When the action involves a well- learned, rehearsed or automatic response, the control operates at a lower level (contention scheduling mechanism) and an appropriate action/response is selected by lateral inhibition of competing response sequences (schemas). Accordingly, there is increased activity in the cortical areas mediating selected schema and decreased activity in the areas representing unselected schemas [e.g., Luck et al., 1990]. When the action/ response is novel or complex, an additional system (supervisory system) is required for selection of a desired response sequence. The central executive is a supervisory system for working memory and it regulates a variety of functions, including (1) directing

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attention to a relevant stimulus and inhibition of irrelevant stimuli, (2) switching attention between different processes, and (3) coding and checking of the contents of memory storage.

ANATOMICAL LOCALIZATION OF EXECUTIVE CONTROL

Neuroimaging experiments have localized several cortical areas that mediate different functions of the central executive. Many investigators have used Stroop tasks for localization of the area that inhibits irrelevant stimuli and directs attention toward the relevant stimulus. Stroop task involves naming color of the ink in a congruent (e.g., the word "red" printed in red color), incongruent (e.g., word "red" printed in blue color), or neutral (a noncolor related word, e.g., "city" printed in any color) condition. In incongruent condition cognitive competition between meaning of the word and the color of ink requires attention to the relevant task (naming the color) and inhibition of the irrelevant task (meaning of the word). A number of recent studies have reported activation of cingulate cortex in Stroop and Stroop-like tasks [Bush et al., 1998; Carter Mintun, and Cohen, 1995; Pardo et al., 1990]. Further, it has been shown that the cingulate has multiple areas of specialization and it mediates a number of cognitive functions [Badgaiyan and Posner, 1998]. In addition to the inhibition of irrelevant response, cingulate is involved in the other executive functions such as error detection and response monitoring [Badgaiyan and Posner, 1998; Dehaene, Posner and Tucker, 1994]. Because of its involvement in multiple functions of the central executive, the cingulate is considered crucial for execution of supervisory function [Posner and DiGirolamo, 1998].

Interestingly, prefrontal cortex has also been implicated in the tasks that require supervisory or executive control. It has been reported by many investigators that a lesion in frontal cortex severely impairs a patient's performance in the tasks that require complex cognitive processing and response inhibition [e.g. Duncan, Burgess, Emslie, 1995]. Further, activation in the prefrontal region has been observed in the experiments that require attention switching between two tasks, or response inhibition [D'Esposito et al., 1995; Jonides et al., 1998]. Many investigators, therefore, believe that the executive processes are mediated by the prefrontal cortex [e.g., Smith and Jonides, 1999].

In an experiment designed to study supervisory attention system, we asked subjects to generate a verb for a given noun and speak it aloud after waiting for a specified time. After each response a feedback marker indicated their performance in time estimation. We observed activation of both prefrontal and cingulate cortex in this experiment [Badgaiyan and Posner, 1998]. The prefrontal activation appeared after ~200 msec of stimulus presentation, whereas the cingulate cortex was not active until ~300 msec. Since the tasks included in the experiment are known to involve supervisory system, it appears that both prefrontal and cingulate cortices are essential components of the system. Further, because the cingulate was recruited ~100 msec after prefrontal cortex, its control is probably dependent on the input from frontal areas.

It has further been observed that the prefrontal cortex has regional specificity for different types of stimuli. Experiments suggest that the tasks involving storage of spatial information activate prefrontal cells in the dorsolateral part, whereas those involving object-storage (e.g., face recognition) activate cells located more ventrally in the prefrontal cortex of a monkey brain [Goldman-Rakic, 1996]. Imaging studies have reported similar regional specificity in human subjects [e.g. Owen et al., 1996]. These studies indicate that prefrontal activation is domain specific; the ventrolateral area mediates object-specific information, whereas dorsal areas support spatial information [Goldman-Rakic, 1996; Smith and Jonides, 1999]. There is, however, an alternate view that suggests that prefrontal areas are organized according to processing specificity [Petrides, 1994]. This view holds that ventrolateral prefrontal regions are concerned with the organization of sequences of behavioral responses and dorsolateral regions are recruited only when the task requires active manipulation and monitoring of information.

Clark and colleagues [1999] have scanned subjects under fixed and variable target conditions. In the fixed target condition, the target was a predesignated word; in the variable target condition, it was a repeating word in the attended color. They found activation in middle frontal gyrus in the variable target condition. The observation is in agreement with the view that prefrontal cortex is organized according to processing specificity. This view predicts activation of ventrolateral prefrontal cortex when response requirements varied during the task. In this experiment, however, activation was observed only in Broadmann's areas (BA) 8 and 9. Other similar experiments have reported additional activity in BA 10, 45, and 46. Clark et al. [1999] have argued that they did not find activation in these additional areas because their experiment did not involve holding information about the temporal order of stimulus code and that the experiments that

require holding of temporal information have obtained additional activity in BA 10 and 45.

Clark et al. [1999] have also reported activity in the supramarginal gyrus of the parietal cortex (BA 40) bilaterally in the variable target condition. Whereas activity in the left BA 40 has been associated with the storage of phonological information [Smith and Jonides, 1999], the function of the right BA 40 is unclear. Activity in this area is reported in the tasks involving explicit [Tulving et al., 1994] or implicit [Badgaiyan et al., 1999] retrieval of verbal information. Presuming storage function of the supramarginal gyrus, Clark et al. [1999] have proposed that updating of stimulus link is mediated via connections between the middle frontal gyrus and the supramarginal gyrus. They also propose a model of the executive control system based on the concept of multimodal convergence zone. This model assumes linkage between an executive control node (in the middle frontal gyrus) and the related stimulus and response representations via multimodal convergence zones located in the posterior parietal and frontal cortices. Although the model is relevant in context of the observations made by Clark et al., additional experimental evidence is necessary to support their assumptions.

EXECUTIVE CONTROL AND IMPLICIT PROCESSES

Executive control is generally discussed with reference only to "willed actions" and conscious processing. It is not known whether the same or a different executive control regulates implicit (nonconscious) processes. Some of these processes involve the same complex cognitive operations that are assumed to involve executive control when accomplished consciously. Studies have shown that under certain experimental conditions, conscious and nonconscious processing produce similar responses [for review see Schacter and Buckner, 1998]. For example, in a word stem completion task, by using same cue (but different set of instructions), it is possible to retrieve previously studied words either consciously or nonconsciously [Squire et al., 1992; Badgaiyan and Posner, 1997]. Serial reaction time task is another example of a condition in which identical responses are produced by conscious or nonconscious processes. The task requires selection of a series of response keys either in a fixed or random sequence. The response latency is shorter when the sequence is fixed. This reaction time advantage is observed both when subjects are consciously aware of the sequence and when they have no awareness [Nissen and Bullemer, 1987]. Under both conditions

similar stimuli produce similar responses. Since the conscious condition involves working memory and requires executive control, it is logical to assume that the nonconscious condition that produces similar response (reaction time advantage) should also be regulated by a central control process because the level of complexity of response execution under the two conditions is similar.

The model of attention for action by Norman and Shallice [1986] assumes that a supervisory attentional system (on which the concept of central executive is based) is required when a response is complex. It further suggests that the activation of supervisory system requires "deliberate attention," implying that the system is recruited only when the action is conscious. For the execution of "automatic" actions, the model proposes a "contention scheduling" mechanism that operates by lateral inhibition of unselected response sequences. However, the automatic action, as defined in this model, does not include complex implicit cognitive functions such as implicit learning and memory. It refers to "routine" motor actions where competitive responses are few and relatively well defined. The model does not explain how the actions associated with the complex implicit processing are executed.

A review of neuroimaging data reveals a similarity in prefrontal involvement in the tasks of working memory, explicit retrieval, and selected implicit processing. Tasks requiring conscious recollection of a list of studied words have consistently been shown to activate the dorsolateral prefrontal cortex [Squire et al., 1992; Schacter et al., 1997], which is implicated in the central executive control of working memory [Goldman-Rakic, 1996; Smith and Jonides, 1999]. Further, these activations are thought to be associated with postretrieval monitoring [Schacter et al., 1997], which is a component of the central executive control [Posner and DiGirolamo, 1998; Smith and Jonides, 1998].

Interestingly, activity in the prefrontal cortex is also observed in some implicit tasks that do not require conscious awareness. Thus increased activity in the dorsolateral prefrontal area (BA 9/46) has been reported by several investigators during implicit motor sequence learning in a serial reaction time task [Rauch et al., 1997]. Another implicit task that activates prefrontal cortex is the cross-modality priming [Badgaiyan, Schacter, and Alpert, 1999; Schacter, Badgaiyan, and Alpert, 1999], which involves nonconscious retrieval of a list of studied words using a cue in a different sensory modality (e.g., visual study and auditory cue or vice versa). Frontal activity, however, has not been observed in implicit tasks that do not require either

motor sequence learning or a modality change between study and test. These tasks actually show reduced activity [Badgaiyan, Schacter, and Alpert, 1999; Buckner et al., 1996] in the ventral prefrontal cortex (BA 9/10), which is implicated in executive control of object based information.

Even though some of the implicit tasks activate the same regions of prefrontal cortex that are involved in central executive processes, it is premature to predict at this point whether (a) these implicit tasks are controlled by the same executive processes that regulate conscious actions, (b) implicit processes that do not require motor sequence learning and modality change operate independent of the central executive processes, or (c) implicit responses are controlled by a separate set of executive mechanism having distinct anatomical location and processing properties.

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