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Research Focus

Extracting core components of cognitive control

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The facility with which humans perform and shift among a wide variety of cognitive tasks seems to indicate a mechanism for entering into a task-dependent mode or set. However, little is known about the neural systems that subserve task control. A recent neuroimaging study by Dosenbach *et al.* offers a set of novel methodological tools to examine this issue and uncovers new candidate brain regions for a core system that might implement task sets.

Introduction

Every experimental researcher who works with humans finds it surprisingly easy to get participants to perform almost any arbitrary cognitive task, even difficult and novel ones, after providing only brief instructions and limited practice. Moreover, once participants start a task, they usually perform with a high degree of accuracy and speed and maintain this performance over long task sessions. Monsell [1] noted that this seemingly mundane and typically unnoticed aspect of experimental research is actually one of the most remarkable unsolved mysteries of human cognition. What are the psychological and neural mechanisms that enable us to encode and maintain task goals and instructions as a 'task set' to ensure high levels of performance across an extended session? A complete answer to this question might not be available for some time; however, the question itself has become the focus of intense research interest. Several experimental tools have been developed to examine processes related to task-level control of cognition. The most common approaches examine effects of performing multiple tasks either in an interleaved fashion (typically referred to as dual-task paradigms) or in a rapid and/or unpredictable sequence (typically referred to as task-switching paradigms). Studies of this type have yielded a wealth of new information, such as evidence of a distinction between transient updating and sustained maintenance of task-set information [2]. Nonetheless, new questions have emerged, such as whether these distinctions are truly domain general (as would be the hallmark of an executive-control process) or present only in certain types of tasks. A recent paper by Dosenbach *et al.* [3] presents an experimental approach to address such questions and provides exciting new data regarding the domain generality of key components of task control.

Temporal dynamics of task-control signals

Dosenbach *et al.* relied on a novel approach to experimental design and analysis of functional magnetic resonance imaging (fMRI) data – the state-item or mixed blocked/event-related design. This approach differs from traditional blocked and event-related designs and enables fMRI researchers to have 'the best of both worlds' by separating out sustained, across-trial signals from transient event-locked signals (Figure 1). Although the mixed design has been used in previous research [4,5], Dosenbach *et al.* extended the utility of the approach by using it to identify three types of signals that might be markers of a task-set implementation system: start-cue signals, sustained signals and error-feedback signals. Then they searched for brain regions that were consistently sensitive to all three signals across a wide variety of tasks. The key finding was that only two regions showed strong evidence of task and control-signal consistency (Figure 2): a medial frontal cortex (MFC) area that comprises the dorsal anterior cingulate cortex and pre-supplementary motor area, and a ventrolateral frontal cortex (VLFC) area that comprises anterior insula and frontal operculum.

This pattern of findings was intriguing in that it did not reveal the 'usual suspects' that are postulated to be involved in the implementation of top-down control of cognition. In particular, prior literature has focused on the dorsolateral and anterior regions of prefrontal cortex (PFC) as being the most crucial for top-down control functions [2,6–8] (although recent work has begun to indicate a role for the VLFC in task-rule representation [9]). Dosenbach *et al.* found that these PFC regions were involved either only in specialized control processes (error activity for dorsolateral PFC) or, in the case of anterior PFC, less consistently than the MFC and VLFC regions. Although recent studies [6] of executive control have highlighted the MFC region identified by Dosenbach *et al.*, a widely held view is that this region has a purely evaluative or monitoring role and is not involved in the top-down implementation of control [10]. However, this view has been questioned [11]. Nevertheless, Dosenbach *et al.* suggest that their results indicate that both the MFC and VLFC are central components of a system for implementing task control in humans. Conversely, they propose that anterior and dorsolateral PFC might be involved in more specialized aspects of control, such as under conditions that have high working-memory demands or when control parameters need to be adjusted on a trial-by-trial basis.

Signatures of task control

The Dosenbach *et al.* study puts forth a clear-cut set of criteria regarding the 'signature' of a core component of human task control and the tools for identifying such signatures. According to the researchers, the MFC and VLFC fit this signature better than other candidate regions

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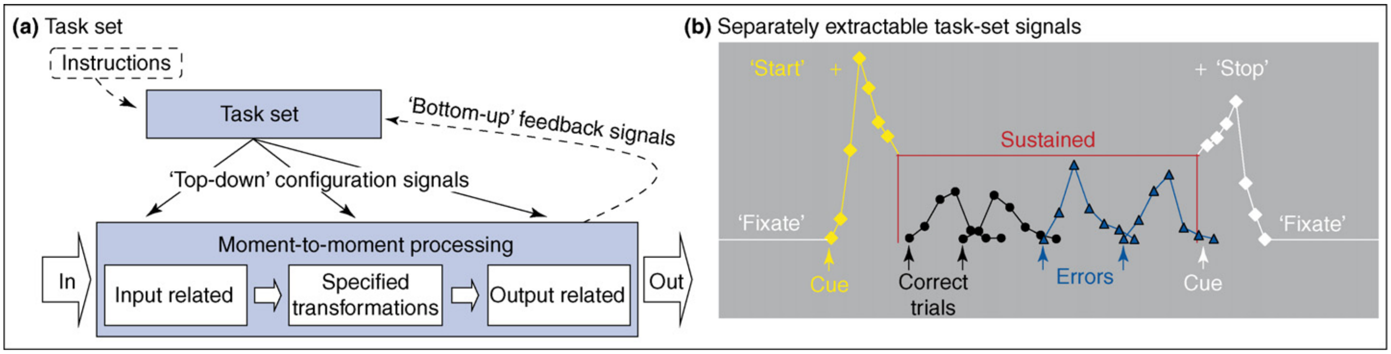

Figure 1. The application of the mixed blocked/event-related design to identify components of a task-set control system. Event-related fMRI provides information about event-locked signals that relate to different trial types or components, but it does not provide information about signals that are not event-locked or that are sustained. By contrast, blocked designs provide an estimate of brain-activity change during an epoch of task performance compared with a baseline, but they combine transient event-locked signals with those that are sustained across the whole epoch. The mixed design differs from event-related and blocked designs because it provides multiple types of brain-activity estimates. **(a)** The theoretical framework of Dosenbach *et al.* [3] in terms of the processes that need to be engaged to instantiate and maintain task sets. **(b)** The signals that can be extracted from a mixed blocked/event-related fMRI design that are relevant to understanding task control: start-cue signals (yellow) at the beginning of a block might represent the loading-in and instantiation of task-set parameters; sustained signals (red) might represent task-set maintenance; and error-feedback signals, which differentiate incorrectly (blue) from correctly (black) performed trials and might reflect monitoring and adjustment of task-set control. Reproduced, with permission, from Ref. [3].

because they show the most consistent activation across studies and control signals. This is a provocative claim that should launch an important new direction for future research. However, the search for cross-task consistency could be a double-edged sword. One might consider regions that exhibit too much consistency in activation patterns to not be satisfactory candidates for involvement in task control if that consistency persists across tasks that vary widely in task-control demands. In particular, a crucial question is whether such active control signals (e.g. task-set maintenance) are needed to perform all cognitive tasks or are required only for tasks in which there is considerable interference or competition for cognitive processing and behavior (i.e. when task goals conflict with bottom-up factors, such as default-action tendencies or perceptually salient aspects of the environment) – the typical markers of cognitive-control demands in many current theories [7,12]. In other words, systematic variation in activation should also be thought of as an important marker of a task-control region. Indeed, Dosenbach *et al.* note that substantial variation and consistency was observed in control-signal activation across tasks (Figure 2). Thus, one key direction for future research will be to examine directly variation in the relationship to task-control demands to determine whether the regions they identified, or others, show a tight coupling between activity and different dimensions of control demand.

Cross-task variation can also be used as a tool to determine whether the control-signal components that were identified by Dosenbach *et al.* represent different dimensions of the same functional mechanism (in which case, systematic covariation among signal types would be expected) or whether they reflect dissociable functions of the same regions. For example, it is possible that phasic (e.g. error-related) and tonic (sustained) signals in the MFC reflect independent functions. This would not be that surprising, given examples of the dissociability of tonic and phasic signals in the nervous system, such as in the midbrain dopamine system, which projects strongly to the MFC [13,14]. A third way to exploit cross-task variation is in studies of functional connectivity. Thus, another marker of a task-control region could be differential connectivity with downstream regions as a function of specific task demands and task content. A finding like this could strengthen claims that regions such as the MFC and VLFC are the source, rather than the site, of top-down control signals.

Task control as generic resource allocation

It is important to consider carefully whether there are alternative interpretations – beyond the implementation of task goals or set – that could account for a signature of strong cross-task and control-signal consistency. One possibility is that this signature might reflect an arousal-related process. Dosenbach *et al.* dismissed this option, but, based on current data, it is unclear whether this dismissal is valid. During cognitive-task performance, it is likely that both task-initiation cues and error cues signal an increase in arousal, which would probably also be maintained at an above-baseline level throughout the duration of the task. At the end of the paper, Dosenbach *et al.* make a similar point when discussing the contrast between a task mode and a default mode (for a default mode, they refer to the consistent sustained deactivation that is exhibited in the ventromedial PFC). The authors argue that the MFC and VLFC might be involved in shifting the brain from a ventromedial PFC-dominated default mode into a task mode, particularly in tasks for which resource allocation and competition is a problem. It is intuitive to think that this form of network dynamics could be mediated by an arousal-related process. Such an interpretation might prompt a reconceptualization of the nature of arousal-type processes, which might include outwardly directed resource allocation as a more generic response to the demand of cognitive-task performance.

Concluding remarks

Dosenbach *et al.* highlight the potential of their approach as a novel method for extracting multiple types of task-control signals from fMRI data. By demonstrating that reliable start-cue, sustained and error signals can be identified consistently across tasks, the authors have validated

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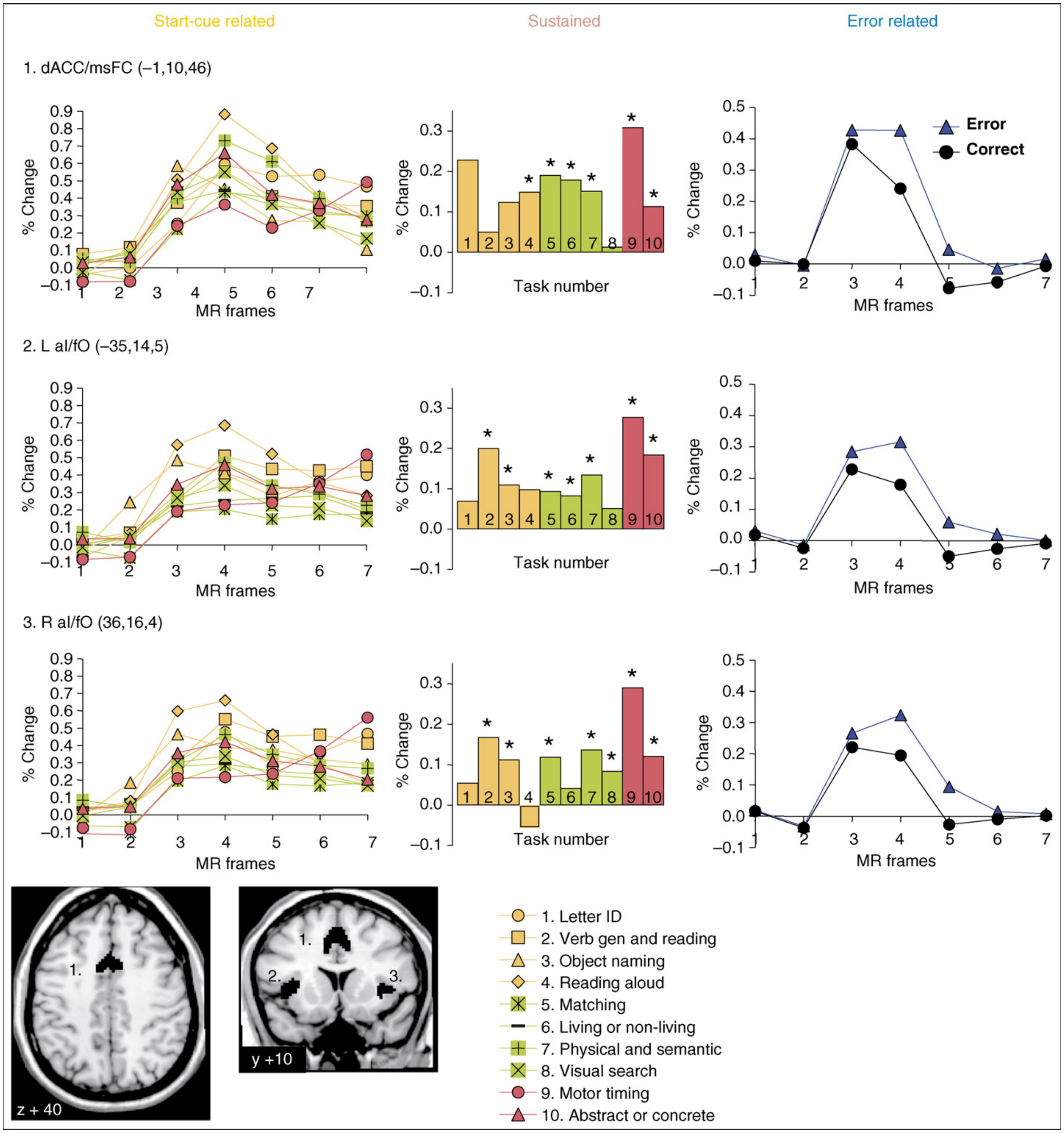

Figure 2. Key findings of Dosenbach *et al.* [3]. The study extracted three types of task-control signals from ten fMRI datasets (listed 1–10) that varied substantially in stimulus modalities (auditory or visual), categories (words, pictures, tones, symbols), task demands (timing, identification, reading, matching, semantic classification) and output requirements (manual or vocal). An overlap analysis was performed to identify regions that were activated consistently across all tasks and for all three task-control signals (start-cue related, sustained and error related), under the assumption that cross-task and cross-signal consistency are key markers of a truly domain-general control process (rather than a task or domain-specific control process). Activation maps reveal that a pattern was observed in the medial frontal cortex (MFC) (dACC/msFC in graph and labeled 1 in images) and bilateral ventrolateral frontal cortex (VLFC) (L aI/fO and R aI/fO in graph and labeled 2 and 3 in image). Graphs illustrate the pattern of activity for the three types of task-control signals in these regions. The first column illustrates event-related responses to the start-cue signal. Start-cue activity was significant in all ten tasks for these regions ($P < 0.001$). The second column illustrates the magnitude estimates for the sustained signal. The asterisks denote which tasks showed significant sustained activity ($P < 0.05$), indicating variability across tasks in the degree to which these regions showed sustained activity. The third column illustrates error-related activity. Abbreviations: MR, magnetic resonance; dACC/msFC, dorsal anterior cingulate cortex/medial superior frontal cortex; aI/fO, anterior insula/frontal operculum. Reproduced, with permission, from Ref. [3].

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the utility of the method. Moreover, the results suggest that the MFC and VLFC subserve crucial task control functions. This study by Dosenbach *et al.* should open up many new lines of research that could help uncover further the nature and dimensions of cognitive-task control.

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