**Review** 



# Frontal Cortex and the Hierarchical Control of Behavior

David Badre<sup>1,2,\*</sup> and Derek Evan Nee<sup>3</sup>

The frontal lobes are important for cognitive control, yet their functional organization remains controversial. An influential class of theory proposes that the frontal lobes are organized along their rostrocaudal axis to support hierarchical cognitive control. Here, we take an updated look at the literature on hierarchical control, with particular focus on the functional organization of lateral frontal cortex. Our review of the evidence supports neither a unitary model of lateral frontal function nor a unidimensional abstraction gradient. Rather, separate frontal networks interact via local and global hierarchical structure to support diverse task demands.

## Cognitive Control and Functional Organization of Frontal Lobes

Humans have an unrivaled ability to envision a desired state of affairs and then carry out the actions to achieve it. This capacity to manage goal-directed behaviors in novel situations, counter to habit, or amidst competing action choices is termed cognitive control [1–3]. In the brain, **cognitive control** (see Glossary) has a close dependency on the frontal lobes and their associated systems [4]. However, there has been persistent controversy regarding the functional organization of the frontal lobes, whether there exist one or more functionally distinct areas or networks, and how these components interact to support controlled behavior.

Here, we take an updated look at an influential class of hypotheses surrounding the **rostrocaudal organization** of function in the frontal lobes. Though several variants of this organizing principle have been proposed (reviewed in [5]), the common element has been that rostral frontal areas are involved in more abstract forms of control than more caudal areas. This putative rostrocaudal abstraction gradient has been theorized to support a hierarchical processing architecture of the frontal lobes, wherein abstract goals are actively translated into movements via a rostral-to-caudal flow of processing, and rostral areas of frontal cortex influence and organize processing in posterior areas [6–8]. The past decade has witnessed numerous tests of these basic hypotheses. Here, we revisit the evidence for a hierarchical organization of the frontal lobes are organized hierarchically, there is likely not a unidimensional gradient of abstraction. Rather, the apex of the hierarchy may be more caudal than previously thought, with rostrolateral prefrontal cortex (RLPFC) supporting a distinct functional role.

## What Is Hierarchical Control?

Much of the evidence informing the rostrocaudal organization of frontal cortex has come from studies examining **hierarchical cognitive control**. In some sense, all cognitive control is hierarchical in that it concerns how top-down contextual signals modulate pathways from stimulus to response. However, hierarchical cognitive control distinguishes those cases wherein actions must be controlled based on immediate contextual signals that are themselves

#### Highlights

It has been proposed that rostral frontal regions support more abstract cognitive control.

Current evidence supports three distinct functional networks supporting sensory-motor control, control based on a present context, and control based on an internal state (schematic control).

However, no single dimension of abstraction defines a gradient across the full rostrocaudal axis of the frontal cortex.

The processing architecture of lateral frontal cortex is hierarchical such that some regions influence others more than vice versa.

Mid-DLPFC, not RLPFC, may be the top of the frontal hierarchy.

RLPFC is important for schematic control.

Corticostriatal circuits may govern hierarchical dynamics among networks.

Motivational signals conveying control demands are tracked via a parallel rostrocaudal organization in the medial frontal cortex, which modulates the intensity of control.

<sup>1</sup>Department of Cognitive, Linguistic, and Psychological Sciences, Brown University, Providence, RI, USA <sup>2</sup>Brown Institute for Brain Science, Brown University, Providence, RI, USA

<sup>3</sup>Department of Psychology, Florida State University, Tallahassee, FL, USA

\*Correspondence: David\_Badre@brown.edu (D. Badre).

170 Trends in Cognitive Sciences, February 2018, Vol. 22, No. 2 https://doi.org/10.1016/j.tics.2017.11.005 © 2017 Elsevier Ltd. All rights reserved.





also influenced by one or more superordinate contexts. Managing these multiple levels of contextual contingency at once introduces special problems for the control system (Box 1).

Hierarchical control applies to multilevel rules that we follow in everyday life. To illustrate, consider the following example (from [9]) (Figure 1A). Children are often taught, 'When inside speak in a soft indoor voice'. Here, being indoors contextualizes how to speak. However, a savvy child quickly learns that the indoor voice rule only applies when a parent is nearby. In this case, the parent provides a superordinate context that determines how other contextual features, like being indoors, should influence behavior. Failing to manage the relationship among these contextual elements properly likely results in a scolding (or wasted effort).

Hierarchical control also contributes to everyday tasks that require taking a series of actions in time. Here, one must simultaneously manage a sequence of subgoals in the context of a superordinate goal. For example (Figure 1B), when taking a shower, people pursue a sequence of subgoals; like washing their hair, then face, and so forth, all under the **temporally abstract** overall goal of getting clean (from [10]). Further, each subgoal must be internally monitored relative to the overall sequential plan because little in the stimulus indicates whether now is the moment to wash one's hair versus clean one's face. Thus, sequential tasks often require **episodic control** wherein a temporal epoch (i.e., episode) serves as the control signal (Figure 1B).

Almost all tasks we do in everyday life have a complex hierarchical structure with multiple levels of goals prevailing over different timescales. Furthermore, structuring a task hierarchically is an effective way to reduce interference among otherwise competing task sets. Indeed, people tend to impose hierarchical structure on tasks even when doing so is unnecessary or costly [11,12]. So, in the world outside the laboratory, hierarchical cognitive control is likely the representative rather than exceptional case for task performance.

It follows that one's capacity for hierarchical control may be particularly important for adaptive behavior. In late childhood to early adolescence, age-related differences in rule-guided behavior can be specifically attributed to a developing ability to handle rules with increasing contingencies [9,13]. Problems with hierarchical control are likewise among the chief complaints of patients with executive function deficits, usually following frontal lobe damage [14–17]. These issues often contrast with these same patients' preserved ability to perform simplified laboratory tests of cognitive control [16,18,19]. Furthermore, hierarchical control problems pose theoretical challenges that may not be solved by straightforward extrapolation from simplified tasks and theory (Box 1). Thus, progress requires experiments that explicitly manipulate hierarchical control demands. Experiments of this type have consistently yielded functional differences along the rostrocaudal axis of frontal cortex; an observation that hints at the importance of this organization for this type of complex control.

## Is there a Rostrocaudal Abstraction Gradient in the Lateral Frontal Cortex?

Although several variants of a rostrocaudal organizing principle have been proposed (reviewed in [5]), the common element has been that rostral frontal areas support more abstract forms of control than caudal areas do. Evidence across species indicates that progress toward the rostral forebrain is marked by change in several anatomical features, including reduced cell density [20,21], diminished intra-areal connectivity [20], greater dendritic spines [22], decreased laminar differentiation [23,24], and longer connectional and synaptic distance from sensory input regions [25]. Theorists have long cited these trends to argue that processing becomes more integrative and abstract toward the rostral forebrain.

## Glossary

**Cognitive control:** general capacity to use an internal contextual representation to guide full pathways of thought and action in accord with goals.

**Contextual control zone:** region of mid-lateral PFC supporting cognitive control of thought or action in the present moment or episode based on internally maintained context representations.

## Domain generality: abstracts over

or is insensitive to differences in input domain.

Episodic control: using a latent state, episode, or temporal context to guide behavior. The term episodic does not imply a necessary relationship to episodic memory, but rather conveys control by episodes or temporal events.

#### Hierarchical cognitive control:

specific case whereby context-action relationships are themselves controlled by one or more superordinate contexts.

Input gate: mechanism to control what information is encoded and maintained in working memory. Output gate: mechanism to select information from within working memory for further processing. Policy: relationship between a context and an appropriate course of

action, akin to a rule.

**Policy abstraction:** degree to which a policy relates contexts to classes of more specific policies.

Relational integration: degree to which separate feature dimensions must be related to one another in order to make a decision.

#### Rostrocaudal organization:

organization of function along a front (rostral) to back (caudal) axis of a brain area.

Schema: superordinate declarative knowledge structure that encodes a large number of lower order features and their relationships, abstracted over multiple experiences.

Schematic control zone: region of rostrolateral PFC involved in control based on superordinate or modelbased knowledge encoded in schemas

Sensory-motor control zone: region of caudal frontal cortex involved in control of effector movements based on basic stimulus-response relationships.



Neuroimaging studies added functional specificity to these foundational ideas [7,26]. For example, one functional magnetic resonance imaging (fMRI) study [26] manipulated the abstractness of stimulus–response rules over four levels. At the simplest level, participants responded based on stimulus–response associations (color–finger). Each subsequent level increased the contextual contingencies to be traversed to select a response (color–feature–finger, color–dimension–feature–finger, episode–color–dimension–feature–finger). Activation in progressively rostral prefrontal cortex (PFC) regions tracked competition at higher levels of the task from dorsal premotor (PMd) to anterior premotor (prePM) to mid-dorsolateral PFC (mid-DLPFC) to RLPFC (Figure 2A). Similar abstraction gradients have been observed in studies preceding and following this one [7,27–35]. These neuroimaging studies gained complementary support from studies of patients with focal brain lesions, who exhibited deficits at a level of complexity commensurate with their lesion and higher, but not lower, levels [36,37]. Collectively, these data support that more abstract control requires progressively rostral frontal cortex.

## Testing Different Forms of Abstraction

These early studies provided a foundation of support for the abstraction hypothesis. However, several different types of abstraction covaried in these experiments [5]. As tasks increased in level, contexts generalized over more rules (**policy abstraction**), more dimensions had to be integrated to make a decision (**relational integration**), and contexts had to be sustained over longer periods of time while lower-order decisions were made (temporal abstraction). Furthermore, other evidence indicated that anterior frontal areas were more **domain general** than caudal areas [38,39]; yet a fourth type of abstraction.

Subsequent attempts to distinguish these forms of abstraction from each other have been largely inconclusive. Although several studies have reproduced rostrocaudal differences [27,29,34,35] (Figure 2B), no single type of abstraction has clearly ranked the hierarchy in a

#### Box 1. Architectures for Hierarchical Control

What special problems do hierarchical control tasks pose? To answer this, it is helpful to first consider a simple model of cognitive control. Figure IA depicts the familiar guided activation model of cognitive control during a Stroop task [91]. Here, control is enacted through a top–down influence from PFC units that maintain the task (i.e., color naming) in a context layer. This top–down signal biases the color-naming pathway to win its competition for responding over habitual word reading.

Figure IB depicts a hierarchical control problem. In this hypothetical task, the participant must respond to either the color or the shape of a final stimulus with their left or right hand. The shape or color task is cued by a preceding number context. However, the interpretation of this number context is itself contextualized by a Greek letter. This third-order rule structure can be expressed as a three level hierarchical tree.

This simple increment in rule complexity makes the control problem much harder. To illustrate, consider how one might modify the model in Figure IA to follow this more complex rule. Even from basic principles of guided activation, there are several qualitatively different ways to solve this problem. The models depicted in Figure IC,D are representative of two such classes of hypothetical solutions.

The network in Figure IC is a unitary hub controller architecture. It does not add any new contextual layers to the architecture in Figure IA. Rather, it follows the rule by increasing dimensionality (i.e., a larger number of units) in the associative and context layers to accommodate the separate pathways without overlap. Of course, this model has limitations. For example, as connected, this model loses the hierarchical structure of the rule by effectively flattening the higher contextual layers. This loss of hierarchical structure can make certain types of generalization and transfer difficult.

Figure ID depicts a hierarchical control architecture. Here, the contextual layer that influences the pathway from low level shape and color inputs to responses is itself controlled by a second network that has access to its own inputs and is influenced by a third contextual layer. Due to their separation, the contextual decisions do not interfere with each other, allowing them to progress in parallel, matching the mostly parallel decision-making dynamics that people exhibit in these higher order rule tasks [92]. Likewise, the network can separately learn when to engage each level of control [93,94]. And, by preserving hierarchical structure, these architectures can rapidly transfer and generalize [11,93–95].

Temporal abstraction: contexts that are sustained in time and abstract over intervening episodes. **12AX task:** standard AX task requires participants to monitor a series of letters for an X that follows an A. The 12AX adds a preceding context, the 1 or 2, that cues whether one monitors for an X following an A or a Y following a B.



Computational models of hierarchical control have largely used hierarchical architectures with separate, interacting context layers [11,94,96,97]. Evidence of rostrocaudal differences in PFC may be in line with the spatially separate controllers required by these architectures. However, others propose that the high dimensional capacity of PFC neural populations [98] can support massive flexibility within a single contextual layer [99]. As noted above, many solutions surely exist to hierarchical control problems, including those not discussed here, such as recurrent networks [100]. However, no model using a nonhierarchical architecture has accounted for the range of effects that hierarchical architectures have captured to date. Nevertheless, as a constraint on theory, it is essential to directly investigate how the brain responds to well-defined hierarchical control problems.



Figure I. Architectures for Hierarchical Control. (A) Schematic of the simple model of the Stroop task from [91]. Thick lines depict stronger connection strength. (B) Task schematic and rule structure for a hierarchical control task. A unitary context hub (C) and a hierarchical control architecture (D) could both solve this problem, though with different strengths and weaknesses.

task-independent way. Furthermore, as tasks have changed, often so have the specific regional associations with different levels of abstraction.

Control over working memory is one task demand that consistently modulates abstractionrelated activation patterns. Working memory is central to cognitive control, as it permits the maintenance of task relevant contextual information over time (Box 1). As detailed in Box 2, managing multiple contexts by choosing items to update or select from within working memory may be a central mechanism of hierarchical control. It follows that demands on these processes





Figure 1. Hierarchical Control Demands Affecting Rostrocaudal Activation. (A) Policy abstraction can be operationalized in terms of the depth of decision tree relating contexts to actions. Here, the presence of a parent contextualizes the relation between the environment and speech volume. (B) Temporal abstraction (red curved arrow) refers to contextual representations that are sustained over time and/or abstract over intervening episodes or subtasks. Here, the goal of 'take shower' abstracts over several subtasks *en route* to the goal of being clean. When a temporally abstract context is used to guide control of lower order tasks, rather than information available in the stimulus, this is referred to as episodic control (brown curved arrows). Thus, if prior steps or the overall structure of a shower plan is referenced to determine what subtask to perform, this is episodic control.

influence the frontal network. Empirically, however, this influence was first noted in an experiment that pitted different types of abstraction against one another, but failed to find abstraction differences in rostral versus caudal PFC at all [40]. This study used a variant of the **12AX task** to distinguish policy versus temporal abstraction. Participants responded according to rules at increasing levels of policy abstraction. Importantly, cues were presented in series so that items could be selectively updated into working memory based on a preceding context.

Many areas of the PFC activated to both abstraction manipulations without regional differentiation. Instead, PFC showed stronger transient responses when contextual information was frequently updated, and stronger sustained responses when contexts persisted across trials. The study concluded that the demand to maintain contexts in working memory determined PFC activity rather than abstraction.





Figure 2. Three Zones of Rostrocaudal Lateral Frontal Organization. (A) Approximate location of anatomical labels defined in the text on an inflated lateral surface. prePMd and prePMv are separately labeled. (B) Small shapes plot locations of peak foci on the lateral surface from studies that located differences in two or more levels of abstraction. Color distinguishes the three functional zones. Small green spheres plot sensory–motor control (or first-order policy). Yellow shapes plot studies manipulating contextual control. Yellow spheres involve second-order control. Studies using third-order policy are diamonds. Maroon shapes plot studies manipulating schematic control regardless of policy level. Large shapes plot means. The mean sensory motor (green sphere: Y = -7) was most caudal. Within the mid-lateral contextual control atomic zones, second- and third-order vellow sphere: Y = 15). However, regardless of policy, schematic control demands shifted activity most rostral (maroon sphere: Y = 49). (C) The 17-network parcellation of resting state from [76]. Colors highlight the networks that roughly corresponds with the three functional zones: schematic (maroon), contextual (yellow), and sensory–motor (green). Abbreviations: mid-DLPFC, mid-dorsolateral prefrontal cortex; prePMd, dorsal anterior (pre) premotor; prePMv, ventral anterior (pre) premotor; RLPFC, rostrolateral prefrontal cortex.

This study highlighted how control of working memory, specifically through updating and maintenance, might impact hierarchical control and accordingly, PFC activation patterns. Nevertheless, there were unique features of this experiment that may have contributed to its observations. For example, even lower order policy conditions required referencing temporally remote cues to interpret the present context (i.e., episodic control). Furthermore, as a block design, activity related to individual cues was not assessed.

More recent studies have used similar serial designs while avoiding these limitations. These studies have located results more in line with the rostrocaudal organization, but also confirm the importance of control over working memory. One such fMRI study [33] also employed a 12AX task, but separately examined activation related to updating the higher- versus lower-order context cue, while minimizing episodic control demands. Updating a lower- versus higher-order context activated caudal PMd versus rostral mid-DLPFC, respectively. These patterns of activation were further distinguishable from response preparation in motor cortex. Thus, this study observed a clear rostrocaudal pattern related to abstraction, but the specific loci of activation were distinct from similar levels of abstraction tested in previous studies.



One possible reason for these differences in locus could relate to demands the serial presentation placed on working memory control. Another fMRI study [41] scanned a modified 12AX task in which the higher-order context could appear before or after the lower-order contextual items (Figure 3). If the higher-order context appeared first, as with [40] and [33], it could be used to update only the relevant lower-order context into working memory; a process termed **input gating**. When the higher-order context appeared last, the candidate lower-order contexts had to be stored in memory, and then selected once the higher-order context appeared; a process termed **output gating**.

More consistent with locations found in previous work [26], this study selectively associated output gating of a second order rule with prePM, rather than areas rostral or caudal. Furthermore, activation in prePM was strongest when the context appeared last versus first. Thus, in contrast to the adaptive maintenance hypothesis [40], it was the demand to use a higher-order context to select a lower-order context from within working memory that elicited activation in the expected prePM region, and not maintenance. Nevertheless, this result also indicates that the dynamics by which contexts are updated and used in working memory will modulate activity patterns in frontal cortex, even when the level of rule abstraction remains constant.

#### Box 2. Orchestrating Network Interactions: Gating and Striatum

Cortico-striatal-thalamic circuits may be central in supporting the network interactions required for hierarchical control. Though direct corticocortical connections could support these interactions, there are computational advantages to separating mechanisms for memory from those enacting selection and updating, sometimes termed gating [101]. Several models associate the striatum with gating as a means of information routing in complex tasks [102–105].

A gate is a mechanism that regulates propagation from one circuit to another. The cortico-striatal-pallidal-thalamic circuit [106,107] has long been associated with motor gating [108], acting as a positive or negative feedback loop for cortically represented actions via disinhibition of the thalamus. Neural network models [96] demonstrate that this circuit could also regulate the gating of working memory during cognitive control. For example, the striatum could support an output gate via thalamocortical amplification of relevant contexts already maintained in PFC.

Multiple lines of evidence from neuroimaging [33,41,109–112], neuropsychology [113], and pharmacological interventions [114–116] support corticostriatal working memory gating. And, though other mechanisms could also support gating, none has explained the range of memory and learning phenomena that are captured by the corticostriatal gate.

This mechanism can be elaborated to support hierarchical control (Figure I; [94,109,117]). For example, higher-order context representations in rostral areas could provide top down signals to caudal corticostriatal loops that regulate output gating of lower-order contexts. Indeed, nesting output gating in this way, rather than input gating, may be particularly advantageous for hierarchical control [94,118].

Fewer studies have directly tested corticostriatal gating during hierarchical control tasks. One such fMRI study observed that the mid-DLPFC increased connectivity with the striatum during input gating of a higher-order cortex [33]. However, premotor increased connectivity with the parietal cortex rather than striatum when updating the lower-order context. A study manipulating both input and output gating similarly found little evidence of corticostriatal input gating of a lower-order context [41]. However, this study did observe evidence of increased prePM-to-caudate connectivity during output gating of the lower-order context; perhaps consistent with the emphasis that modeling has placed on output gating during hierarchical control.

There is also preliminary support for multiple interacting corticostriatal loops. Reward prediction errors related to learning a second order rule modulated fMRI activation in the prePMd and a spatially proximate subregion of the caudate nucleus [93]. A study using a hierarchical artificial grammar task [119] showed that three separate pairs of lateral frontal cortex and striatal foci were activated by increasing levels of the task, and each shared white matter connections. Furthermore, high-fidelity diffusion tractography indicates that not only are frontostriatal connections finely topographically organized rostrocaudally, but where they diverge from this pattern, they are more likely to do so from the rostral PFC to caudal striatum [120], in line with asymmetric top-down influences (Figure I).



Corticostriatal interactions may be crucial for hierarchical control. However, gating mechanisms need not be exclusive to hierarchical control architectures, they could also be applied to unitary context layers. Thus, regardless of the specific architecture, corticostriatal output gating may be an important part of the mechanism by which hierarchical control is enacted.



Figure 1. Schematic of Elaboration of the Contcostriatal Model for Hierarchical Control. Details of the corticostriatal loops are simplified to emphasize the nested looping structure. Each loop regulates a separate region of frontal cortex. Striatal components of each lower orderloop receive top down context information from higher order areas of FC through diagonal connections (red arrows). Abbreviations: CN, caudate nucleus; GP, globus pallidus; prePMd, dorsal anterior (pre) premotor cortex.

To summarize, demands on working memory gating may be crucial factors in how regions rostral-to-caudal are engaged, over and above manipulations of abstraction. Gates that regulate input and output of working memory are likely important in hierarchical control tasks that require relating separate contextual elements to each other, and so may be core mechanisms of hierarchical cognitive control (see Box 2).

## The Difficulty with 'Difficulty'

An important alternative to the abstraction hypothesis is the difficulty hypothesis. From this perspective, more rostral frontal cortex is activated as tasks become more difficult. Supporting this view, an fMRI study [42] examined PFC activity while participants identified the shortest among a set of visually presented lines across conditions that varied in their difficulty. Relative to a baseline, each of the difficulty manipulations increased activity in the PFC as far rostral as the right RLPFC. The mechanisms underlying these manipulations were not specified. Nevertheless, as the difficulty of a perceptual discrimination does not ostensibly vary with abstraction, the authors concluded that PFC is sensitive to task difficulty, not abstraction.

Yet, the difficulty account is hard to reconcile with the broader body of evidence for functional differences along the lateral frontal cortex (Figure 2B). For example, it is unclear why updating a higher-order context cue would be more difficult than a lower-order response cue, even though the former activates a more rostral site [33]. The fMRI study already discussed that found a rostrocaudal gradient associated with increasingly abstract rules [26] also found that task difficulty, as indexed by response time, could not explain their results. A combined fMRI/ transcranial magnetic stimulation (TMS) study [10] tested a hierarchical sequential task and observed the RLPFC to be least activated at the first sequence position, although behaviorally, this position had the longest response time [10,43]. An fMRI study of effective connectivity during hierarchical control [34] observed the RLPFC in their delay condition that required





Figure 3. Gating Refers to Input and Output from Working Memory. (Top) Updating information into working memory is input gating. Selecting information from within working memory to guide action is output gating. (Bottom) A second-order rule from [37] uses a higher-order context (number) to decide which lower-order context (letter or wingding) is used in a final match decision (red box indicates correct response). The order of second- and first-order contexts determines gating demands. When a second-order context comes first, the relevant first-order context can be input gated. When it comes last, the first-order context must be output gated from working memory.

holding a sequence position pending. Although involving episodic control, this was the easiest condition in the experiment based on performance. Thus, although difficulty undoubtedly affects activity in PFC, it is likely the mechanisms that the PFC supports to overcome that difficulty that determines the rostrocaudal activity pattern.

## Diverse Functions of the RLPFC

Function of the RLPFC is central to any account of the rostrocaudal organization of the PFC. The RLPFC has been consistently distinguished from mid-lateral and caudal portions of the PFC when some form of episodic or temporally abstract control is required (Figure 2B). The RLPFC is active and necessary when participants have to use a temporal context to guide interpretation of the stimulus context [7,26,27,35,44]. It is also consistently activated when participants hold a pending goal in mind while performing a subtask [30,34] or prospectively planning a task [45–47].

However, RLPFC activation is also observed under conditions that are not readily described in terms of temporal or episodic control. For example, studies continue to associate the RLPFC with relational integration tasks that require integrating multiple stimulus dimensions (e.g., [48]). Also, this association is evident even when pitted against maintenance of a (nonintegrated) cue over a delay [35].

Furthermore, a growing body of evidence has found that RLPFC regions are consistently active when alternative courses of action are merely considered [49]. For example, the RLPFC has been associated with strategic choices to explore versus exploit [50–52], such as by tracking the relative uncertainty of an unexplored option [50]. Similarly, RLPFC may track alternative task sets during learning, allowing for new task set discovery [53].



Finally, the RLPFC shows a terminal position preference during sequential tasks that is not readily explained as episodic control [54]. In an fMRI experiment [10], participants were required to repeatedly perform two categorization tasks (a color or shape judgment) in a four-task sequence (e.g., color, shape, shape, and color). No cues indicated which task to perform on any trial, so the sequence order had to be internally sustained and episodic control was required uniformly throughout. Yet, the RLPFC ramped its activation over the course of the task sequence, with its peak activity at the terminal position of the sequence. Others have observed similar terminal position effects during variable length sequences [55]. Furthermore, TMS of the RLPFC, but not mid-DLPFC or rostral-medial PFC, induced errors at the end of the sequence [10]. Perhaps relatedly, the sole electrophysiological recording study from monkey frontal pole located strategy-selective cell firing at the end of the trial sequence, during feedback [56].

Thus, the RLPFC appears engaged under conditions requiring abstract superordinate knowledge of current and hypothetical task states, pending states, and future goals; this includes, but is not exclusive to, tasks requiring episodic control.

## **Beyond Gradients: Three Frontal Cortical Zones**

In summary, we find limited evidence supporting any single dimension that forms a gradient over lateral frontal cortex, whether that dimension is one particular type of abstraction or global difficulty. However, this is not to say that there are no functional distinctions along the rostrocaudal axis of frontal cortex. On the contrary, the evidence appears to consistently support three major functional subdivisions (Figure 2B).

The most caudal subdivision includes motor and premotor cortex and is generally related to **sensory-motor control** of effector movements. While movements are commonly considered the output of control processes (i.e., controlled behavior), the ability to sustain working memory may leverage effector systems (e.g., frontal eye fields for spatial working memory) [57,58]. Within this zone, motor and premotor subregions hold a hierarchical relationship to one another in the representation of movement [59,60]. There is also evidence for domain specificity within this zone, such as with respect to spatial versus verbal information along a dorsal/ventral divide [34].

More rostral, the mid-lateral PFC zone is related to **contextual control** of behavior in the present moment or episode. This zone is associated with diverse task demands, including most conventional cognitive control tasks, and it overlaps the lateral PFC component of the multiple demand system [61,62]. More controversially, within this zone, there may be at least two subregions: prePM and mid-DLPFC [7,26,41]. The evidence distinguishing these regions has mostly come from studies manipulating policy abstraction (Figure 2B). This relationship may be due to the demands abstract policy places on working memory gating. However, policy abstraction has not been systematically distinguished from other factors in these areas. For example, there is some evidence that the more caudal subregions are more domain specific than the mid-DLPFC [34]. Nevertheless, these separate areas might provide spatially distinct pools of neurons to support hierarchical control based on separate representations of multiple contexts, above the sensory–motor level (Box 1).

Finally, the most rostral zone includes RLPFC and represents a range of control signals that we term **schematic control** in order to convey its generality beyond only temporal or episodic signals. Bartlett [63] coined the term **schema** as a knowledge structure that organizes many lower-order features and their relationships. In essence, schemas are models of the world and ourselves in it. Recently, schemas have gained renewed focus in memory systems research



[64,65], where their retrieval and use have been associated with interactions between rostral ventromedial PFC (vmPFC) and hippocampus [64,66]. Schema representations in vmPFC support knowledge of sequential structure (e.g., [67]), as well as memory-based inferences, such as transitivity among associates [68]. Likewise, vmPFC may represent a cognitive map of the latent task space that people can reference to make decisions and learn [69]. Finally, this system has been implicated in episodic future planning, wherein people imagine specific images of future events and goals [70].

RLPFC is consistently engaged when control depends on an episodic or temporally structured context, integration and inference over multiple features, and when tracking hypothetical strategies, goals, and pending states. These types of control broadly depend on the structured information that schemas are proposed to hold. RLPFC also shares close anatomical connections with vmPFC [71,72], and so it may be well positioned to transmit internal schematic knowledge retrieved by the vmPFC–hippocampal system to the PFC as a control signal. In line with this hypothesis, it was recently observed that the strength of fMRI classifier evidence for a future goal in hippocampus correlated with the strength of activation in RLPFC [73].

The extrinsic connectivity of the frontal lobe largely fits with this functional organization. Evidence from the nonhuman primate indicates that the PFC can be organized along dorsal and ventral architectonic trends [23,24], with some also distinguishing a further caudal zone [74,75]. Five pathways connect the dorsal trend with posterior neocortex and four connect the ventral trend. These pathways transmit uni- and multimodal information to the frontal cortex. Roughly, the primary termination of these sensory pathways tends to be in caudal frontal areas up to area 9/46, with the more rostral areas, like area 46, receiving these inputs indirectly via intrinsic frontal connections or through the cingulate fasciculus. Furthermore, posterior dorsal regions supporting spatial representations, like the dorsal parietal cortex, tend to connect with the dorsal caudal frontal cortex, while ventral temporal regions processing objects and verbal-semantic information connect with ventral frontal areas. Thus, these connectivity patterns generally align with the observation that caudal areas of PFC are relatively more domain specific and may have closer proximity to the input than rostral ones. However, RLPFC may be similar to these caudal regions in that it shares strong primary connections with vmPFC regions that are important for internally generated schematic knowledge.

This tripartite division between sensory-motor, contextual, and schematic control fits with the heuristic that more rostral areas support more abstract representations. However, these zones are functionally discontinuous, violating a linear, progressive rostrocaudal gradient. Rather, they may overlap with distinct functional networks, such as those identified from a parcellation of resting state functional connectivity [76] (Figure 2C). As such, each zone correlates with distinct areas outside of the lateral frontal cortex, including medial frontal (Box 3), parietal, and temporal lobe structures. Thus, the functional distinctions drawn here may apply to these distributed networks more broadly.

## **Processing Architecture of Lateral Frontal Cortex**

If these distinct zones or networks operate together as a hierarchical control architecture, then there should be evidence that rostral, superordinate regions influence caudal, subordinate regions during hierarchical control tasks [6,7]. An intracranial recording study in humans [77] provided evidence for such interregional dynamics during hierarchical control. Four patients with implanted subdural grids overlying lateral frontal cortex performed the first three levels of the hierarchical control task previously associated with rostrocaudal differences using fMRI [26]. As the policy level increased, theta-gamma phase-amplitude coupling increased both



within the PFC and between the PFC and premotor/motor electrodes. Furthermore, a directional analysis indicated that PFC theta-phase encoding was a stronger predictor of the premotor/motor gamma modulation than the reverse. The precise physiological correlate of these oscillatory signals is still a matter of open research [78,79]. However, these results provide evidence that hierarchical control demands modulate rostro-to-caudal inter-regional dynamics.

Of course, a frontal processing hierarchy predicts a deeper, multilevel architecture than was tested in this study. For example, the cascade model [7] proposed that hierarchical control is supported by a propagation of top–down control signals from rostral to caudal areas. The RLPFC might form the apex of the frontal hierarchy and influence the mid-DLPFC, which influences the prePM, and so forth toward the motor cortex. Support for this model has come from structural equation modeling of fMRI connectivity showing the anticipated top–down cascade, although the RLPFC was not explicitly examined. Likewise, an initial review of monkey anatomy suggested that the RLPFC might be the apex [80].

Recent evidence, however, has called the idea of an RLPFC apex into question. An extensive meta-analysis of monkey anatomical projections focused on connectional asymmetry. Based on a proposal by Badre and D'Esposito [80], any area higher in the hierarchy might exert asymmetrical influence, with broader efferent connections to lower order (i.e., caudal) areas than the reverse. Thus, if it is the apex, the RLPFC should show the highest connectional asymmetry. However, among lateral PFC regions, anterior mid-DLPFC (areas 45 and 46) showed the greatest asymmetry, while the RLPFC (area 10) was average on this metric [81].

#### Box 3. Gradient in the Dorsomedial Frontal Cortex

A synergistic role between the lateral and dorsomedial PFC has long been a staple of theories of cognitive control. For example, adding a conflict monitor to Figure IA in Box 1 that detects coactivation in the response layer and relays this response conflict to the context layer enables dynamic control that simulates trial-by-trial adjustments made in humans [121]. Under this framework, the context layer corresponds to the lateral PFC, while the conflict monitor corresponds to the dorsomedial PFC [122, 123]. More recently, as the lateral PFC has been fractionated into subdivisions, so too has the medial PFC.

Paralleling the lateral PFC, demands on sensory-motor control tend to elicit activity in the caudal supplementary motor area (SMA), while demands on contextual control engage the more rostral preSMA [124] and dorsomedial PFC. More broadly, gradients along the medial wall have been observed in decision-making contexts, with progressively rostral medial PFC areas computing progressively abstract signals related to competition at the level of responses, decisions, and strategies [125], which have point-by-point interactions with corresponding lateral PFC areas [126,127].

Dorsomedial PFC areas are particularly sensitive to rewards/penalties [128,129], with the preSMA showing signals reflecting immediate, contextual incentives, and the more rostral dorsal anterior cingulate cortex showing signals reflecting tonic, episodic incentives [130]. These dorsomedial PFC signals have been shown to interact with lateral PFC regions sensitive to contextual and episodic control, respectively, and so may provide motivational signals that selectively upregulate control processes in these lateral PFC zones [130]. Similar point-by-point interactions between the dorsomedial and lateral PFC have been observed when prediction errors require updating of control representations at different levels of abstraction [131]. Collectively, these data indicate a parallel structure between the lateral and dorsomedial PFC.

Numerous modeling efforts have sought to understand the computations performed by the dorsomedial PFC [121,132– 134], but few have attempted to incorporate its rostrocaudal structure. A recent exception is the hierarchical error representation model [132]. Under this model, the fundamental role of the dorsomedial PFC is to learn to predict outcomes given the representations retained in the lateral PFC. Distinct medial-lateral layers correspond to first-, second-, and third-order contingencies linking responses to outcomes. Hierarchical control emerges from a cascade of rostral-to-caudal signals whereby rostral dorsomedial PFC areas diagonally influence adjacent caudal lateral PFC areas, modulating representations therein (Figure I). Conversely, performance feedback reverses these dynamics whereby



prediction errors update lateral PFC representations and dorsomedial PFC outcome predictions in a caudal-to-rostral manner (Figure I). Collectively, these dynamics allow the model to learn what information is useful to remember to successfully complete complex, hierarchical control problems. The model makes testable predictions of medial-lateral PFC interactions that can guide future research.



Figure I. Model Schematics Showing Top–Down versus Feedback Processing in the Medial–Lateral Hierarchical Architecture from [97]. Abbreviations: cLPFC, caudal lateral prefrontal cortex; cMFC, caudal medial frontal cortex; mLPFC, mid-lateral prefrontal cortex; mMFC, mid-medial frontal cortex; rLPFC, rostral lateral prefrontal cortex.

This study did note that a laminar definition of hierarchy [82], rather than connectional asymmetry, would place RLPFC closer to the top. However, effective connectivity from human fMRI has provided convergent evidence that the mid-DLPFC, rather than RLPFC, may be the apex of a frontal processing hierarchy.

In a recent fMRI study [34], dynamic causal modeling was used to study effective connectivity during a hierarchical control task. Univariate activity dissociated regions along the rostrocaudal PFC in accord with the tripartite division we label here as schematic, contextual, and sensory-motor control. A stimulus-domain manipulation identified dorsal (human frontal eye fields) and ventral (inferior frontal junction) frontal regions within the caudal sensory-motor zone sensitive to spatial versus verbal information, respectively. Importantly, during periods of minimal cognitive control demands, hierarchical strength, defined again based on greater outward than inward effective connectivity, progressed from a reversed input pattern (greater inward than outward connectivity) for the most caudal sensory-motor regions to positive for the caudal



mid-lateral regions [ventral anterior (pre) premotor cortex (prePMv) and dorsal anterior (pre) premotor cortex (prePMd)] to maximal for rostral mid-DLPFC. However, hierarchical strength then dropped in the RLPFC to the reversed (input > output) level, akin to the most caudal sensory–motor regions.

Cognitive control demands modulated these dynamics. The overall pattern was hierarchical such that the apical mid-DLPFC region exerted a domain-general influence on the domain-specific prePMd and prePMv regions. These caudal contextual control regions also received domain-specific input from the sensory-motor regions. Similarly, the mid-DLPFC received input from the RLPFC during conditions of schematic control. Collectively, these dynamics demonstrate the integration of inputs from sensory-motor areas (sensory) and RLPFC (schematic), with hierarchical control between the mid-DLPFC and prePM. A subsequent fMRI/TMS experiment has replicated these effects and found that behavioral changes following stimulation were consistent with this pattern of information flow [83].

## **Conclusions: Revised Framework for Hierarchical Control**

A long-standing question in the study of cognitive control has concerned whether the frontoparietal control system is best conceptualized as a unitary controller or if it possesses a meaningful functional organization. This debate has been complicated by further controversy over the catalog of executive functions and their nonspecific mapping to regions within this network. The literature reviewed here is inconsistent with any fully unitary view. Likewise,



#### Trends in Cognitive Sciences

Figure 4. Schematic Summary of the Functional Relationships among Regions of Frontal Cortex. Regions within the schematic (maroon), contextual (yellow), and sensory-motor (green) control zones are labeled along with their respective influences. Heavy, unbroken black arrows show primary direction of influence, based on structural and effective connectivity. Broken black arrows show weaker influences. Colored arrows show task-dependent, domain-specific influences. The architecture features both global and local hierarchical relations, with the contextual control zone influencing the other zones, and then further local hierarchy within the contextual and sensory-motor zones. Individual regions also differ in domain specificity or proximity to different domain influences. Abbreviations: FEF, frontal eye field; IFJ, inferior frontal junction; mid-DLPFC, mid-dorsolateral prefrontal cortex; prePMd, dorsal anterior (pre) premotor cortex; prePMv, ventral anterior (pre) premotor cortex; RLPFC, rostrolateral prefrontal cortex.



proposals of a unidimensional rostrocaudal gradient of abstraction or processing hierarchy also require revision.

We propose that the anterior mid-DLPFC, rather than RLPFC, is the apex of the frontal control hierarchy (Figure 4). The RLPFC is best characterized as a domain-specific frontal region, with a role analogous to caudal domain-specific frontal regions. The RLPFC input domain, however, is internal schema-based knowledge, possibly transmitted from the vmPFC and its associated network. When demands on cognitive control arise during a task, sensory information from posterior areas converges with schematic information from the RLPFC in the mid-lateral contextual control zone. These regions support cognitive control generally, however, the local relationship between the mid-DLPFC and prePM, and then premotor and motor cortex within each zone, is hierarchical. Interactions between these areas or networks, as well as their broader outputs to the brain, may be learned and coordinated via gating computations carried out by local cortico-striatal-thalamic loops (Box 2). Motivational, conflict, and/or error signals conveying control demands are tracked via medial frontal cortex, which modulates intensity of control by these lateral frontal zones (Box 3).

Thus, returning to the examples at the outset of this paper, cases like following complex rules or taking a shower require multiple levels of context to be managed at once. In the present framework, these multiple contextual elements can be updated and maintained separately by different lateral frontal networks running from the mid-DLPFC to prePM and premotor to motor cortex, depending on (i) the type of control (sensory-motor or contextual) and (ii) the level and domain (verbal/spatial/schematic) of contextual contingency to be monitored. Higher-order contingencies are processed more rostrally within these zones. To the degree that control depends on temporal episodes, pending tasks, or future and alternative courses of action, the RLPFC may be important for processing and transmitting this information to the control hierarchy, potentially to the highest level in the mid-DLPFC. In our example of taking a shower, for instance, the RLPFC might track an episodic code that can be referenced as needed to select the correct subgoal at sequence boundaries in the absence of any cues in the environment to do so.

This model subtly contrasts with the perspective of the mid-lateral PFC as an amodal hub. The mid-lateral PFC is activated across a range of task demands and may be important in rapidly orchestrating broader network dynamics to perform a diverse range of tasks [62,84–88]. These observations are not inconsistent with the framework we present here. The overall output from broad contextual control zone could support these diverse demands. Furthermore, due to their placement, caudal prePM areas might be engaged by more tasks.

However, it is important to distinguish that no single area appears to act as an amodal hub. The apical region of the mid-DLPFC is not engaged by simple control problems [7,26,41]. Also, it may not be characterized as a hub in the network sense. Goulas *et al.* [74] did not find that their apical areas 45 and 46 were hubs as assessed by betweenness centrality (although see [75]). Likewise, most structural connectivity metrics do not assign a particularly high hub score to any mid-lateral PFC region relative to other areas of the frontal lobe [89]. Rather, the mid-DLPFC might exert its influence via the other lower-order frontal regions: a hierarchical rather than hub-like network position. More posterior contextual control regions (e.g., prePM) might better resemble hubs in that input from both the mid-DLPFC and the caudal sensory–motor regions converge on them [34]. Likewise, as contextual information propagates through the hierarchy, caudal areas lower in the hierarchy might receive a more specific mixture of accumulated contextual information, perhaps consistent with evidence from fMRI multivoxel classifier



analysis [90]. However, given their domain sensitivity, they would be expected to be involved variably across different tasks, unlike an amodal hub. Thus, although the overall mid-lateral contextual control zone is perhaps multiple demand and hub-like when considered as a broad zone, this character may emerge from a local hierarchical processing architecture that changes dynamics among regions in a task-dependent way.

We expect this framework to undergo further revision as we gain new observations regarding the connectivity between networks and regions (see Outstanding Questions). It will be important to understand how specific demands, like working memory gating or learning, change these network relationships. Also, given the complex tasks required to expose these relationships, more mechanistic theory is needed addressing hierarchical control problems.

In conclusion, research on hierarchical cognitive control prompts departure from both unitary theories and unidimensional abstraction gradients. Rather, the frontal lobes are a dynamic system with several different local networks that interact at a systems level to carry out complex tasks. These networks influence each other through both local and global hierarchical structure, forming a processing architecture capable of enacting complex hierarchically structured rules. This architecture supports our ability to flexibly behave in a complex world.

#### Acknowledgments

This work was supported by the National Institute of Mental Health (MH111737, MH099078), a MURI award from the Office of Naval Research (N00014-16-1-2832), and an award from the James S. McDonnell Foundation. We are grateful to Mark D'Esposito, Michael Frank, Christopher Chatham, Theresa Desrochers, Will Alexander, and Apoorva Bhandari for helpful comments and discussions on these topics, and to Charles Badland and Eun Young Choi for help with the illustrations.

#### References

- Duncan, J. et al. (1996) Intelligence and the frontal lobe: the 13. Unger, K. et al. (2016) Working memory gating mechanisms organization of goal-directed behavior, Cogn. Psychol, 30, 257-303
- 2. Logan, G.D. and Gordon, R.D. (2001) Executive control of visual attention in dual-task situations. Psychol. Rev. 108, 393-434
- 3. Miller, E.K. and Cohen, J.D. (2001) An integrative theory of prefrontal cortex function. Annu. Rev. Neurosci. 24, 167-202
- Stuss, D.T. and Benson, D.F. (1987) The frontal lobes and 4. control of cognition and memory. In The Frontal Lobes Revisited (Perecman, E., ed.), pp. 141-158, IRBN Press
- Badre, D. (2008) Cognitive control, hierarchy, and the rostro-5. caudal organization of the frontal lobes. Trends Cogn. Sci. 12, 193-200
- Fuster, J.M. (2001) The prefrontal cortex an update: time is of 6. the essence. Neuron 30, 319-333
- Koechlin, E. et al. (2003) The architecture of cognitive control in the human prefrontal cortex. Science 302, 1181-1185
- 8 functional organization: Philos, Trans, R. Soc, Lond, B Biol, Sci. 360, 781-795
- Amso, D. et al. (2014) Working memory updating and the 9. development of rule-guided behavior. Cognition 133, 201-210
- 10. Desrochers, T.M. et al. (2015) The necessity of rostrolateral prefrontal cortex for higher-level sequential behavior. Neuron 87. 1357-1368
- 11. Collins, A.G. and Frank, M.J. (2013) Cognitive control over learning: creating, clustering, and generalizing task-set structure. Psychol. Rev. 120, 190-229
- 12. Collins, A.G.E. (2017) The cost of structure learning. J. Cogn. Neurosci. 29, 1646-1655

- explain developmental change in rule-guided behavior. Cognition 155, 8-22
- 14. Duncan, J. (1986) Disorganization of behaviour after frontal lobe damage. Cogn. Neuropsychol. 3, 271-291
- 15. Goel, V. et al. (2013) Lesions to right prefrontal cortex impair real-world planning through premature commitments. Neuropsychologia 51, 713-724
- 16. Shallice, T. and Burgess, P.W. (1991) Deficits in strategy application following frontal lobe damage in man. Brain 114, 727-741
- 17. Zanini, S. et al. (2002) Action sequencing deficit following frontal lobe lesion. Neurocase 8, 88-99
- 18. Burgess, P.W. et al. (1998) The ecological validity of tests of executive function. J. Int. Neuropsychol. Soc. 4, 547-558
- 19. Eslinger, P.J. and Damasio, A.R. (1985) Severe disturbance of higher cognition after bilateral frontal lobe ablation: patient EVR. Neurology 35, 1731-1741
- Petrides. M. (2005) Lateral prefrontal cortex: architectonic and 20. Finlay, B.L. (2016) Principles of network architecture emerging from comparisons of the cerebral cortex in large and small brains, PLoS Biol. 14, e1002556
  - Thiebaut de Schotten, M. et al. (2017) Rostro-caudal architec-21. ture of the frontal lobes in humans. Cereb. Cortex 27, 4033-4047
  - 22. Jacobs, B. et al. (2001) Regional dendritic and spine variation in human cerebral cortex: a quantitative golgi study. Cereb. Cortex 11 558-571
  - 23. Sanides, F. (1972) Representation of the cerebral cortex and it areal lamination pattern. In The Structure and Function of the Nervous System (Bourne, G.H., ed.), pp. 329-453, Academic

#### **Outstanding Questions**

How does the brain solve hierarchical control problems? This is the topic of this review, but our review has also made clear that more studies are needed that directly address hierarchical control demands, like policy and temporal abstraction, and the influence of schematic knowledge. Simplified tasks may not expose the dynamics of the control system, whereas complex tasks without clear mechanisms challenge interpretation. More data are needed from hierarchical control tasks with clear operational definitions and interpretable mechanisms.

To what degree do the systems-level dynamics reviewed here generalize across tasks? What is their underlying neurophysiological basis? How do broader cortical and subcortical structures, like the thalamus or parietal cortex. contribute to these dynamics? More studies of anatomical and effective connectivity during hierarchical control tasks are needed, including using approaches beyond fMRI.

What is the relationship between the local hierarchical control structure of the frontal cortex and broader brain networks dynamics required to carry out a task? Recent efforts applying control and graph theoretic concepts to cognitive control at a systems level may help answer this question.

How do learning and experience impact the hierarchical functional organization of the frontal lobes? There is evidence that the network relationships among frontal regions we review here change with experience. Future studies may inform both the dynamics of this frontal processing architecture, as well as how subcomponents, like striatum, may shape the learning process.

What are the mechanisms of working memory gating? Gating may be central for hierarchical control, but its mechanism - whether cortico-cortical, cortico-striatal-thalamic, or both remains controversial. Research on the neural dynamics of working memory gating will inform our understanding of hierarchical control and the network dynamics in the system we review here.



- 24. Yeterian, E.H. et al. (2012) The cortical connectivity of the prefrontal cortex in the monkey brain. Cortex 48, 58–81
- Margulies, D.S. et al. (2016) Situating the default-mode network along a principal gradient of macroscale cortical organization. Proc. Natl. Acad. Sci. U. S. A. 113, 12574–12579
- Badre, D. and D'Esposito, M. (2007) Functional magnetic resonance imaging evidence for a hierarchical organization of the prefrontal cortex. J. Cogn. Neurosci. 19, 2082–2099
- Bahlmann, J. *et al.* (2015) The rostro-caudal axis of frontal cortex is sensitive to the domain of stimulus information. *Cereb. Cortex* 25, 1815–1826
- Barbalat, G. *et al.* (2011) Impaired hierarchical control within the lateral prefrontal cortex in schizophrenia. *Biol. Psychiatry* 70, 73–80
- Barbalat, G. et al. (2009) Organization of cognitive control within the lateral prefrontal cortex in schizophrenia. Arch. Gen. Psychiatry 66, 377–386
- 30. Koechlin, E. et al. (1999) The role of the anterior prefrontal cortex in human cognition. *Nature* 399, 148–151
- Koechlin, E. and Hyafil, A. (2007) Anterior prefrontal function and the limits of human decision-making. *Science* 318, 594–598
  Koechlin, F. and Jubault, T. (2006) Broca's area and the hierar-
- Noecimin, L. and dubatit, 1. (2000) bloca states and the metalchical organization of human behavior. *Neuron* 50, 963–974
  Nee, D.E. and Brown, J.W. (2013) Dissociable frontal-striatal
- and frontal-parietal networks involved in updating hierarchical contexts in working memory. *Cereb. Cortex* 23, 2146–2158
- **34.** Nee, D.E. and D'Esposito, M. (2016) The hierarchical organization of the lateral prefrontal cortex. *Elife* 5
- Nee, D.E. et al. (2014) Prefrontal cortex organization: dissociating effects of temporal abstraction, relational abstraction, and integration with FMRI. Cereb. Cortex 24, 2377–2387
- Azuar, C. et al. (2014) Testing the model of caudo-rostral organization of cognitive control in the human with frontal lesions. *Neuroimage* 84, 1053–1060
- Badre, D. et al. (2009) Hierarchical cognitive control deficits following damage to the human frontal lobe. *Nat. Neurosci.* 12, 515–522
- Courtney, S.M. et al. (1997) Transient and sustained activity in a distributed neural system for human working memory. *Nature* 386, 608–611
- Sakai, K. and Passingham, R.E. (2003) Prefrontal interactions reflect future task operations. *Nat. Neurosci.* 6, 75–81
- Reynolds, J.R. *et al.* (2012) The function and organization of lateral prefrontal cortex: a test of competing hypotheses. *PLoS One* 7, e30284
- **41.** Chatham, C.H. *et al.* (2014) Corticostriatal output gating during selection from working memory. *Neuron* 81, 930–942
- Crittenden, B.M. and Duncan, J. (2014) Task difficulty manipulation reveals multiple demand activity but no frontal lobe hierarchy. *Cereb. Cortex* 24, 532–540
- Schneider, D.W. and Logan, G.D. (2006) Hierarchical control of cognitive processes: switching tasks in sequences. J. Exp. Psychol. Gen. 135, 623–640
- Bahlmann, J. et al. (2015) Transcranial magnetic stimulation reveals complex cognitive control representations in the rostral frontal cortex. *Neuroscience* 300, 425–431
- Gilbert, S.J. (2011) Decoding the content of delayed intentions. J. Neurosci. 31, 2888–2894
- Momennejad, I. and Haynes, J.D. (2012) Human anterior prefrontal cortex encodes the 'what' and 'when' of future intentions. *Neuroimage* 61, 139–148
- Volle, E. et al. (2011) The role of rostral prefrontal cortex in prospective memory: a voxel-based lesion study. *Neuropsychologia* 49, 2185–2198
- Parkin, B.L. *et al.* (2015) Dynamic network mechanisms of relational integration. *J. Neurosci.* 35, 7660–7673
- Mansouri, F.A. et al. (2017) Managing competing goals a key role for the frontopolar cortex. Nat. Rev. Neurosci. 18, 645–657

- Badre, D. et al. (2012) Rostrolateral prefrontal cortex and individual differences in uncertainty-driven exploration. *Neuron* 73, 595–607
- Boorman, E.D. et al. (2009) How green is the grass on the other side? Frontopolar cortex and the evidence in favor of alternative courses of action. *Neuron* 62, 733–743
- Daw, N.D. et al. (2006) Cortical substrates for exploratory decisions in humans. Nature 441, 876–879
- Donoso, M. et al. (2014) Human cognition. Foundations of human reasoning in the prefrontal cortex. Science 344, 1481–1486
- Desrochers, T.M. et al. (2015) The monitoring and control of task sequences in human and non-human primates. Front. Syst. Neurosci. 9, 185
- Farooqui, A.A. et al. (2012) Hierarchical organization of cognition reflected in distributed frontoparietal activity. J. Neurosci. 32, 17373–17381
- Tsujimoto, S. et al. (2010) Evaluating self-generated decisions in frontal pole cortex of monkeys. Nat. Neurosci. 13, 120–126
- Nee, D.E. and D'Esposito, M. (2015) Working memory. In Brain Mapping. In An Encyclopedic Reference (Toga, A.W., ed.), pp. 589–595, Academic Press: Elsevier
- Buchsbaum, B.R. and D'Esposito, M. (2008) Short-term and working memory systems. In *Learning and Memory: A Comprehensive Reference* (Byrne, J.H., ed.), pp. 237–260, Adacemic Press
- Buch, E.R. et al. (2010) A network centered on ventral premotor cortex exerts both facilitatory and inhibitory control over primary motor cortex during action reprogramming. J. Neurosci. 30, 1395–1401
- Picard, N. and Strick, P.L. (2001) Imaging the premotor areas. Curr. Opin. Neurobiol. 11, 663–672
- Duncan, J. (2013) The structure of cognition: attentional episodes in mind and brain. *Neuron* 80, 35–50
- Fedorenko, E. et al. (2013) Broad domain generality in focal regions of frontal and parietal cortex. Proc. Natl. Acad. Sci. U. S. A. 110, 16616–16621
- 63. Bartlett, F.C. (1932) Remembering, Cambridge University Press
- Gilboa, A. and Marlatte, H. (2017) Neurobiology of schemas and schema-mediated memory. *Trends Cogn. Sci.* 21, 618–631
- Moscovitch, M. *et al.* (2016) Episodic memory and beyond: the hippocampus and neocortex in transformation. *Annu. Rev. Psychol.* 67, 105–134
- Ghosh, V.E. *et al.* (2014) Schema representation in patients with ventromedial PFC lesions. *J. Neurosci.* 34, 12057–12070
- Hsieh, L.T. and Ranganath, C. (2015) Cortical and subcortical contributions to sequence retrieval: Schematic coding of temporal context in the neocortical recollection network. *Neuroimage* 121, 78–90
- Zeithamova, D. *et al.* (2012) Hippocampal and ventral medial prefrontal activation during retrieval-mediated learning supports novel inference. *Neuron* 75, 168–179
- Schuck, N.W. et al. (2016) Human orbitofrontal cortex represents a cognitive map of state space. Neuron 91, 1402–1412
- Schacter, D.L. et al. (2007) Remembering the past to imagine the future: the prospective brain. Nat. Rev. Neurosci. 8, 657– 661
- Averbeck, B.B. and Seo, M. (2008) The statistical neuroanatomy of frontal networks in the macaque. *PLoS Comput. Biol.* 4, e1000050
- Markov, N.T. et al. (2014) A weighted and directed interareal connectivity matrix for macaque cerebral cortex. Cereb. Cortex 24, 17–36
- Brown, T.I. *et al.* (2016) Prospective representation of navigational goals in the human hippocampus. *Science* 352, 1323– 1326
- Saleem, K.S. et al. (2014) Subdivisions and connectional networks of the lateral prefrontal cortex in the macaque monkey. J. Comp. Neurol. 522, 1641–1690



- Blumenfeld, R.S. et al. (2017) Quantitative anatomical evidence for a dorsoventral and rostrocaudal segregation within the nonhuman primate frontal cortex. J. Cogn. Neurosci. 1–12
- Yeo, B.T. et al. (2011) The organization of the human cerebral cortex estimated by intrinsic functional connectivity. J. Neurophysiol. 106, 1125–1165
- Voytek, B. *et al.* (2015) Oscillatory dynamics coordinating human frontal networks in support of goal maintenance. *Nat. Neurosci.* 18, 1318–1324
- Cole, S.R. and Voytek, B. (2017) Brain oscillations and the importance of waveform shape. *Trends Cogn. Sci.* 21, 137–149
- Jones, S.R. (2016) When brain rhythms aren't 'rhythmic': implication for their mechanisms and meaning. *Curr. Opin. Neurobiol.* 40, 72–80
- Badre, D. and D'Esposito, M. (2009) Is the rostro-caudal axis of the frontal lobe hierarchical? *Nat. Rev. Neurosci.* 10, 659–669
- Goulas, A. *et al.* (2014) Mapping the hierarchical layout of the structural network of the macaque prefrontal cortex. *Cereb. Cortex* 24, 1178–1194
- Barbas, H. and Rempel-Clower, N. (1997) Cortical structure predicts the pattern of corticocortical connections. *Cereb. Cor*tex 7, 635–646
- Nee, D.E. and D'Esposito, M. (2017) Causal evidence for lateral prefrontal cortex dynamics supporting cognitive control. *Elife* 6, http://dx.doi.org/10.7554/eLife.28040
- Cole, M.W. et al. (2016) Activity flow over resting-state networks shapes cognitive task activations. *Nat. Neurosci.* 19, 1718– 1726
- Cole, M.W. et al. (2013) Multi-task connectivity reveals flexible hubs for adaptive task control. Nat. Neurosci. 16, 1348–1355
- Cole, M.W. et al. (2012) Global connectivity of prefrontal cortex predicts cognitive control and intelligence. J. Neurosci. 32, 8988–8999
- Bertolero, M.A. *et al.* (2015) The modular and integrative functional architecture of the human brain. *Proc. Natl. Acad. Sci. U.* S. A. 112, E6798–E6807
- Yeo, B.T. et al. (2015) Functional specialization and flexibility in human association cortex. Cereb. Cortex 25, 3654–3672
- van den Heuvel, M.P. and Sporns, O. (2013) Network hubs in the human brain. *Trends Cogn. Sci.* 17, 683–696
- Nee, D.E. and Brown, J.W. (2012) Rostral-caudal gradients of abstraction revealed by multi-variate pattern analysis of working memory. *Neuroimage* 63, 1285–1294
- Cohen, J.D. *et al.* (1990) On the control of automatic processes: a parallel distributed processing account of the Stroop effect. *Psychol. Rev.* 97, 332–361
- Ranti, C. *et al.* (2015) Parallel temporal dynamics in hierarchical cognitive control. *Cognition* 142, 205–229
- Badre, D. and Frank, M.J. (2012) Mechanisms of hierarchical reinforcement learning in cortico-striatal circuits 2: evidence from fMRI. Cereb. Cortex 22, 527–536
- Frank, M.J. and Badre, D. (2012) Mechanisms of hierarchical reinforcement learning in corticostriatal circuits 1: computational analysis. *Cereb. Cortex* 22, 509–526
- 95. Badre, D. et al. (2010) Frontal cortex and the discovery of abstract action rules. Neuron 66, 315–326
- O'Reilly, R.C. and Frank, M.J. (2006) Making working memory work: a computational model of learning in the prefrontal cortex and basal ganglia. *Neural Comput.* 18, 283–328
- Alexander, W.H. and Brown, J.W. (2015) Hierarchical error representation: a computational model of anterior cingulate and dorsolateral prefrontal cortex. *Neural Comput.* 27, 2354– 2410
- Rigotti, M. et al. (2013) The importance of mixed selectivity in complex cognitive tasks. *Nature* 497, 585–590
- Fusi, S. et al. (2016) Why neurons mix: high dimensionality for higher cognition. Curr. Opin. Neurobiol. 37, 66–74

- 100. Song, H.F. et al. (2016) Training excitatory-inhibitory recurrent neural networks for cognitive tasks: a simple and flexible framework. PLoS Comput. Biol. 12, e1004792
- Hochreiter, S. and Schmidhuber, J. (1997) Long short-term memory. *Neural Comput.* 9, 1735–1780
- 102. Frank, M.J. and O'Reilly, R.C. (2006) A mechanistic account of striatal dopamine function in human cognition: psychopharmacological studies with cabergoline and haloperidol. *Behav. Neurosci.* 120, 497–517
- Helie, S. et al. (2015) A neurocomputational model of automatic sequence production. J. Cogn. Neurosci. 27, 1412–1426
- 104. Kriete, T. et al. (2013) Indirection and symbol-like processing in the prefrontal cortex and basal ganglia. Proc. Natl. Acad. Sci. U. S. A. 110, 16390–16395
- 105. Stocco, A. et al. (2012) Distinct contributions of the caudate nucleus, rostral prefrontal cortex, and parietal cortex to the execution of instructed tasks. Cogn. Affect. Behav. Neurosci. 12, 611–628
- 106. Alexander, G.E. et al. (1986) Parallel organization of functionally segregated circuits linking basal ganglia and cortex. Annu. Rev. Neurosci. 9, 357–381
- 107. Haber, S.N. (2003) The primate basal ganglia: parallel and integrative networks. J. Chem. Neuroanat. 26, 317–330
- Mink, J.W. (1996) The basal ganglia: focused selection and inhibition of competing motor programs. *Prog. Neurobiol.* 50, 381–425
- Chatham, C.H. and Badre, D. (2015) Multiple gates on working memory. *Curr. Opin. Behav. Sci.* 1, 23–31
- 110. Cools, R. et al. (2007) Impulsive personality predicts dopaminedependent changes in frontostriatal activity during component processes of working memory. J. Neurosci. 27, 5506–5514
- 111. D'Ardenne, K. et al. (2012) Role of prefrontal cortex and the midbrain dopamine system in working memory updating. Proc. Natl. Acad. Sci. U. S. A. 109, 19900–19909
- 112. McNab, F. and Klingberg, T. (2008) Prefrontal cortex and basal ganglia control access to working memory. *Nat. Neurosci.* 11, 103–107
- 113. Baier, B. et al. (2010) Keeping memory clear and stable the contribution of human basal ganglia and prefrontal cortex to working memory. J. Neurosci. 30, 9788–9792
- 114. Cools, R. and D'Esposito, M. (2011) Inverted-U-shaped dopamine actions on human working memory and cognitive control. *Biol. Psychiatry* 69, e113–e125
- 115. Frank, M.J. et al. (2004) By carrot or by stick: cognitive reinforcement learning in parkinsonism. Science 306, 1940–1943
- Moustafa, A.A. et al. (2008) A dopaminergic basis for working memory, learning and attentional shifting in Parkinsonism. Neuropsychologia 46, 3144–3156
- 117. Hazy, T.E. *et al.* (2006) Banishing the homunculus: making working memory work. *Neuroscience* 139, 105–118
- Reynolds, J.R. and O'Reilly, R.C. (2009) Developing PFC representations using reinforcement learning. *Cognition* 113, 281– 292
- 119. Jeon, H.A. *et al.* (2014) Functional network mirrored in the prefrontal cortex, caudate nucleus, and thalamus: high-resolution functional imaging and structural connectivity. *J. Neurosci.* 34, 9202–9212
- Verstynen, T.D. et al. (2012) Microstructural organizational patterns in the human corticostriatal system. J. Neurophysiol. 107, 2984–2995
- 121. Botvinick, M.M. *et al.* (2001) Conflict monitoring and cognitive control. *Psychol. Rev.* 108, 624–652
- Kerns, J.G. *et al.* (2004) Anterior cingulate conflict monitoring and adjustments in control. *Science* 303, 1023–1026
- MacDonald, A.W., 3rd et al. (2000) Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science 288, 1835–1838



- 124. Korb, F.M. et al. (2017) Hierarchically organized medial frontal 129. Sallet, J. et al. (2007) Expectations, gains, and losses in the cortex-basal ganglia loops selectively control task- and response-selection. J. Neurosci. 37, 7893-7905
- strategic control: evidence for a functional topography in dorsomedial prefrontal cortex. J. Neurosci. 29, 13158-13164
- 126. Blumenfeld, R.S. et al. (2013) Lateral prefrontal cortex is organized into parallel dorsal and ventral streams along the rostrocaudal axis. Cereb. Cortex 23, 2457-2466
- 127. Taren, A.A. et al. (2011) A parallel functional topography between medial and lateral prefrontal cortex: evidence and implications for cognitive control. J. Neurosci. 31, 5026-5031
- 128. Jessup, R.K. et al. (2010) Error effects in anterior cingulate cortex reverse when error likelihood is high. J. Neurosci. 30, 3467-3472
- anterior cingulate cortex. Cogn. Affect. Behav. Neurosci. 7, 327-336
- 125. Venkatraman, V. et al. (2009) Resolving response, decision, and 130. Kouneiher, F. et al. (2009) Motivation and cognitive control in the human prefrontal cortex. Nat. Neurosci. 12, 939-945
  - 131. Zarr, N. and Brown, J.W. (2016) Hierarchical error representation in medial prefrontal cortex. Neuroimage 124, 238-247
  - 132. Alexander, W.H. and Brown, J.W. (2011) Medial prefrontal cortex as an action-outcome predictor. Nat. Neurosci. 14, 1338-1344
  - 133. Behrens, T.E. et al. (2007) Learning the value of information in an uncertain world. Nat. Neurosci. 10, 1214-1221
  - 134. Holroyd, C.B. and Coles, M.G.H. (2002) The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. Psychol. Rev. 109, 679-709