

HUMAN PREFRONTAL CORTEX: PROCESSING AND REPRESENTATIONAL PERSPECTIVES

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Through evolution, humans have acquired ‘higher’ cognitive skills — such as language, reasoning and planning — and complex social behaviour. Evidence from neuropsychological and neuroimaging research indicates that the prefrontal cortex (PFC) underlies much of this higher cognition. A number of theories have been proposed for how the PFC might achieve this. Although many of these theories focus on the types of ‘process’ that the PFC carries out, we argue for the validity of a representational approach to understanding PFC function.

Although it is clear that the PFC is important for higher cognitive skills, particularly in humans, how it achieves these functions is unknown. The human PFC is not necessarily larger than that of other primate species¹, but its neural architecture is probably more sophisticated or organized differently to accommodate higher cognitive functions that are superior to those of related species^{2,3}. Researchers have proposed a number of theories of PFC function, many of which centre around the representations or processes that are mediated by the PFC. We define representations as memories that are localized in neural networks that encode information and, when activated, enable access to this stored information. Processes, on the other hand, are computational procedures or algorithms that are localized in neural networks and are independent of the nature or modality of the stimulus that is being processed. In a representational viewpoint, processes are simply a set of representations that remain activated over a period of time. In this review, we propose five criteria that we believe a theory should meet if it is to provide a useful framework for the understanding of PFC function. We briefly describe the biology and structure of the PFC, and introduce the competing representational and processing viewpoints. After briefly summarizing the primary theories of PFC function, we assess the extent to which they meet these criteria. Although this is not an exhaustive review, we aim to provide a balanced overview of extant theories.

The first of our five proposed criteria is that a theory must be explicit about the information that is stored in the PFC. Does it store information akin to a memory function (representational approach)? Does it store algorithms or computational procedures only for manipulating information stored elsewhere in the brain (processing approach)? Does it do a combination of these things (hybrid approach)? Second, the theory must be consistent with our knowledge of stimulus representation in the brain. If it is not, then the authors must have explained the inconsistency and provided evidence to support its validity. Third, it must be reasonable from an evolutionary perspective (as defined below). Fourth, it must make predictions that enable verification and invalidation of the model. Fifth, it must be supported by the available physiological data — neuroimaging, electrophysiology, and animal and human lesion research.

Biology, structure and evolution of the PFC
The PFC can be divided into ventromedial and dorsolateral regions, each of which is associated with posterior and subcortical brain regions (FIG. 1). The ventromedial PFC has reciprocal connections with brain regions that are associated with emotional processing (amygdala), memory (hippocampus) and higher-order sensory processing (temporal visual association areas), as well as with dorsolateral PFC. The dorsolateral PFC has

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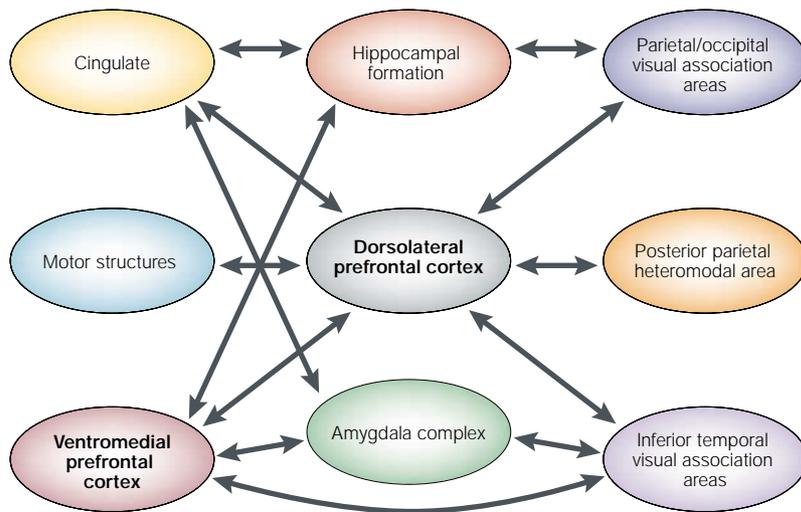


Figure 1 | A summary of the connectivity between prefrontal cortex and other brain regions. The ventromedial and dorsolateral prefrontal cortices exhibit reciprocal connectivity with different posterior brain regions, with ventromedial prefrontal regions being associated with emotional processing areas (for example, amygdala) and dorsolateral prefrontal regions with non-emotional sensory and motor areas (for example, basal ganglia and parietal cortex). Modified, with permission, from REF. 107 © 1999 Guilford Press.

reciprocal connections with brain regions that are associated with motor control (basal ganglia, premotor cortex, supplementary motor area), performance monitoring (cingulate cortex) and higher-order sensory processing (association areas, parietal cortex). The ventromedial PFC is well suited to support functions involving the integration of information about emotion, memory and environmental stimuli, and the dorsolateral PFC to support the regulation of behaviour and control of responses to environmental stimuli.

Neurons in the PFC are particularly able to fire over extended periods of time⁴ and across events^{5,6}. This indicates that the PFC can maintain stimulus representations across time⁷, enabling a subject to engage in behaviour to achieve long-term goals. In addition, pyramidal cells in the macaque PFC are more spinous — and so can handle more excitatory inputs — than other cortical pyramidal cells⁸. This is one structural explanation for the PFC's ability to integrate inputs from many sources and to implement more abstract behaviours. The monkey's PFC contains cells that respond to both internally generated and observed behaviours — these have been termed mirror neurons⁹. Similar regions have been shown to be activated in humans when observing and performing actions^{10,11}. These data support a role for the PFC in the representation of action. Furthermore, Williams and colleagues have suggested that abnormal development of the PFC might lead to impaired social behaviour¹², which can also be caused by PFC damage later in life.

It is thought that the dorsolateral PFC evolved from motor regions and developed much later than the ventromedial PFC^{13,14}. Motor regions store motor programs; it seems reasonable, therefore, that the functions of the 'newer' PFC regions would be related to those of older PFC regions (that is, they are representational). This also supports the idea that the dorsolateral PFC is

involved in representing cognitive action¹⁴. Given the gradual nature of evolution, we believe that a dramatic shift from representation to a computational function would be unlikely. Rather, it seems likely to us that the PFC stores memory representations — over the course of evolution, these became capable of representing more complex behaviours or behaviours that occurred over a longer period of time. It might be possible that a processing perspective can be accounted for within the evolution of the PFC; however, such a perspective has not, to our knowledge, been articulated and is, in our opinion, inconsistent with the prevalent views of the evolutionary development of the PFC.

Our selective overview and interpretation of the neurophysiology and evolutionary data is consistent with the points of view taken by theorists from both sides of the debate. In summary, the connectivity of the PFC regions, physiological properties of its neurons, and evolutionary principles are strongly suggestive of its role in the integration of sensory and memory information and in the representation and control of actions and behaviour. Any theory of PFC function should be consistent with these roles.

Representation versus processing

It has been suggested that "it is difficult to interpret prefrontal deficits without reference to some form of memory" and "the evolution of a capacity to guide behaviour by representation of stimuli rather than by the stimuli themselves introduces the possibility that concepts and plans can govern behaviour"¹⁵. But, traditionally, PFC function in humans has been studied using a processing approach. The processing approach takes the view that cognition in the PFC can be described in terms of performance without specifying the representation that underlies these 'processes'. This approach is a fundamental shift away from how cognitive neuroscientists have previously tried to understand information storage in memory and indicates that the PFC, in contrast to posterior cortex, might have minor neural commitment to long-term storage of knowledge.

The representational approach, by contrast, seeks to establish the form in which information is stored in the PFC. This approach is much closer to how we seek to understand the functions of posterior cortex¹⁴ — similar ideas of representation have dominated the scientific understanding of face, word and object recognition and are accepted descriptions of how features of information are stored and interrelated. In this sense, PFC representations would store elements of knowledge. When activated, these representations correspond to a unique brain state that is signified by the strength and pattern of neural activity. The representation is a 'permanent' unit of memory that can be modified by repeated exposure to similar knowledge elements; it is a member of a local psychological and neural network that is composed of many similar representations. Accordingly, 'processes' in cognition are a set of representations that, when activated, remain activated over a period of time — a possibility that is supported by data showing sustained firing by PFC neurons.

This enables the PFC to code, store and retrieve the more abstract features of behaviours whose goal or end-stage would occur well after a time that exceeds the limits of consciousness in ‘the present’^{16,17}.

We believe that the representational approach to studying the functions of the human PFC is preferable because it forces investigators to define, in detail, the nature of memories stored in the PFC, which leads to a description of the cognitive architecture that is ideally suited to hypothesis testing. Although processes can be studied by emphasizing performance-based analyses, this level of analysis is much harder to constrain theoretically. The primary, current models of the functions of the PFC emphasize representations or processes or are hybrids. Below we consider whether the models are sufficient to address the five criteria we outlined above as being necessary for a comprehensive theory of PFC function.

Adaptive coding model

The adaptive coding model¹⁸ proposes that WORKING MEMORY, attention and cognitive control are subserved by a common underlying process. This is due to the highly adaptable nature of PFC neurons in coding task-relevant information to provide a temporary, task-specific, context-dependent operating space. The operating space is a temporary state, as the same neurons will code different aspects of a situation if the task or context changes and provides a mechanism for SELECTIVE ATTENTION. By selecting the inputs that are most task-relevant, the PFC focuses processing in posterior cortical regions on task-relevant representations. Duncan¹⁸ proposes that there is variation in the flexibility of PFC neurons in coding particular types of information and that not all neurons can represent all task features to the same extent. Rather, he suggests that overlapping regions of PFC are selective to different task demands. Although Duncan uses the term ‘representation’ in reference to the PFC in his model, these representations are temporary and the purpose of the PFC is to provide a flexible means to guide activation of representations stored elsewhere in the brain. This is not consistent with our earlier definition of representations as stored memories. This viewpoint is a processing approach and is consistent with sustained firing of PFC neurons and with a role for the PFC in selecting and integrating sensory information. It is unclear how this model fits in with neurophysiological and evolutionary ideas of action representation and memory integration within the PFC. It is also unclear how task-relevancy of information is determined and how processing in the PFC is coordinated with that in posterior cortex and subcortical regions.

Duncan’s model proposes that PFC neurons should be involved in almost all tasks with little functional specialization between PFC regions¹⁸ — a claim that is based primarily on electrophysiological studies showing task-specific activity in a large proportion of PFC neurons across a variety of tasks¹⁹ and stimulus domains^{19–21}. He also presents neuroimaging data from 20 studies to demonstrate the involvement of specific PFC regions in a diverse collection of tasks — perception, response

selection, language, memory retrieval and problem solving¹⁸. However, a more comprehensive survey of 275 neuroimaging studies into PFC function²² has demonstrated consistent differences in PFC localization between different functions, such as attention, EPISODIC MEMORY, working memory, language and SEMANTIC MEMORY (FIG. 2). Furthermore, some electrophysiological studies have demonstrated response selectivity to particular tasks^{23–25} or stimulus types^{25,26}. Therefore, support for the adaptive coding model is mixed.

Attentional control model

Norman and Shallice’s model of attentional control proposes that there are two mechanisms that monitor behaviour^{27,28}. The contention scheduler results in automatic PRIMING of stored knowledge and the supervisory attentional system (SAS) controls the setting of priorities for action. The SAS reflects conscious awareness rather than simple responses to stimuli. The SAS is localized in the PFC; however, the localization of the contention scheduler is unspecified. The SAS can override the contention scheduler when necessary — for example, the ring of a telephone will cause priming of ‘answer the phone’ behaviour by the contention scheduler, but it might be appropriate for the SAS to override this if the telephone belongs to someone else. While there is limited discussion of representation-like components, such as action schemas, the attentional control model focuses on mechanistic procedures rather than information storage and therefore can be considered to be a processing viewpoint. It is consistent with the functions of behavioural control that are indicated by the biology and structure of the PFC. However, it is unclear how the model relates to the integration of sensory and memory information and to the neurophysiological properties of PFC neurons, and how it fits with our ideas of the PFC’s evolution.

Damage to the SAS should result in distractibility, owing to the dominance of the contention scheduler and impaired behavioural control. Although there is much evidence that damage to the PFC has these effects^{14,29,30}, the model proposes that the SAS is strongly biased towards novel situations for which no behavioural template (schema) is available. This would predict that routine behaviour should not be disrupted by PFC damage. Neuropsychological research has shown that knowledge about routine behaviour is impaired following PFC lesions^{31,32} and neuroimaging research has shown that the PFC is involved in event knowledge^{33–35}. In addition, novel tasks activate anterior PFC, but overlearned tasks activate medial and slightly more posterior PFC regions³⁶. These data are inconsistent with this theory’s predictions.

The SAS is composed of subprocesses that are localized in dissociable PFC regions. These include strategy generation, episodic memory retrieval, error monitoring, problem solving and intention generation. However, the model does not specify which regions are implicated in these processes. There is evidence of different PFC regions being implicated in different processes: for example, error monitoring (anterior cingulate)^{37–39},

WORKING MEMORY

Activated long-term memory.

SELECTIVE ATTENTION

Ability to focus mental effort on a subset of all available information.

EPISODIC MEMORY

Memory for specific events that are temporally dated; includes the relationships between different events.

SEMANTIC MEMORY

Memory for factual information about the world, concepts and word meaning.

PRIMING

Increased accessibility of information as a result of previous exposure to similar information.

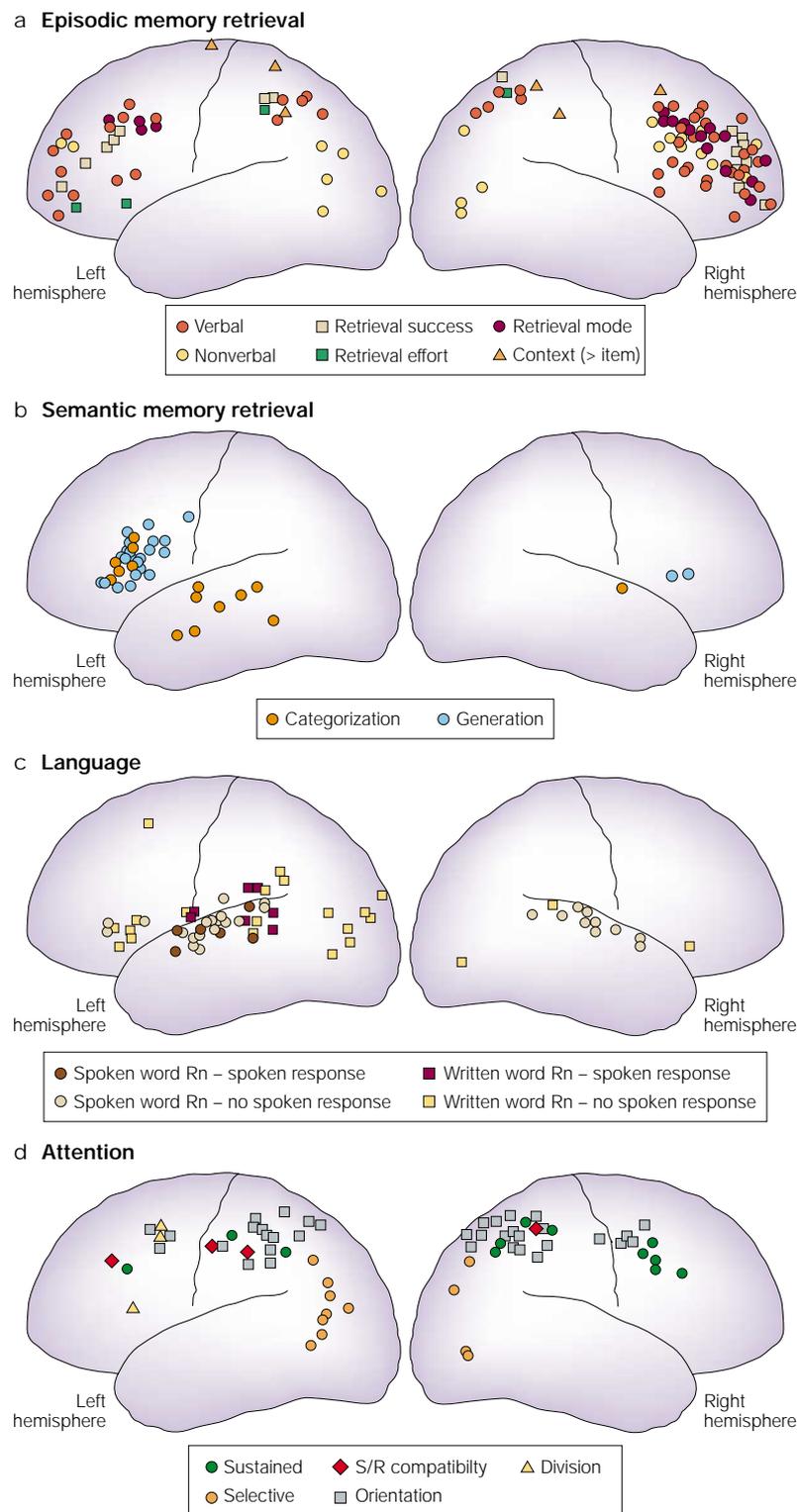


Figure 2 | Prefrontal cortex regions implicated in different functions by neuroimaging studies. **a** | Episodic retrieval. **b** | Semantic tasks. **c** | Language. **d** | Attention. These functions are associated with different patterns of prefrontal cortex activation — within each function, the different tasks that have been imaged are shown in boxes. Comparing the different functions (episodic retrieval, semantics, language and attention), it is clear that they are associated with different patterns of activation. These data are inconsistent with the adaptive coding model's proposal that the same regions of the prefrontal cortex perform different functions. > item, context memory (where, when, how) effect > context memory (what) effects; Rn, recognition; S/R, stimulus/response. Modified, with permission, from REF. 22 © 2000 MIT Press.

episodic memory retrieval (dorsolateral PFC)^{40–42} and problem solving (anterior PFC)^{43–45}. These data are consistent with the broad claims of the model. However, without detailed *a priori* hypotheses regarding the nature of how these processes are represented in the PFC, experimental data will be unable to verify the model.

Connectionist model

Burnod and colleagues proposed a connectionist model of cerebral cortex function in which the PFC is crucial for the acquisition and expression of complex behaviour^{46,47}. The model considers four levels of the cortical system — cell, module, tissue and global — that integrate learning experiences to produce a coherent functional system⁴⁶. The levels have different functions: the cellular level processes information and modifies neuronal behaviour; the modular level enables computation and learning within a cortical column; the tissue level activates different inputs in parallel and integrates successive learning experiences; and the global level integrates functions from different cortical regions to produce behaviour. Different levels of the cortical system would be accessible to different extents by available methodologies; for example, the global and tissue levels might be well suited to investigation by neuroimaging and neuropsychological approaches, whereas the cellular and modular levels might be better suited to investigation using electrophysiology.

In this connectionist model, the PFC integrates sensory inputs and motor information; it stores information about past events; it modulates behaviour on the basis of past experience, current motivation and available reinforcement; and it is important for structured learning and temporal processing. This viewpoint is representational and is consistent with the structure, connectivity, neurophysiology and evolution of the PFC. However, although the model specifies a hierarchy in PFC organization, it does not elaborate on the nature of this hierarchy. This view proposes that units in the PFC correspond to specific sensory or motor events of a specific behaviour and are selective for event sequence⁴⁷. Neuropsychological, electrophysiological and functional magnetic resonance imaging (fMRI) data showing the PFC's involvement in action and event knowledge are consistent with this perspective^{9,11,32–34,48–52}.

The model provides an overview of cortical function and a useful framework in which to consider the contributions of different functional levels of the cortex. However, the model is very broad and does not lend itself well to specific hypothesis testing.

Structured event complex framework

Our structured event complex (SEC) framework proposes that the PFC stores unique forms of knowledge⁵³. An SEC is a goal-oriented set of events that is structured in sequence and represents thematic knowledge, morals, abstractions, concepts, social rules, event features, event boundaries and grammars. The stored characteristics of these representations form the bases for the strength of representation in memory and the relationships between SEC representations. Aspects of SECs are represented

independently but are encoded and retrieved as an episode. The SEC framework is a representational viewpoint that makes specific predictions regarding the properties and localization of SECs in the PFC (FIG. 3).

Maintenance of SEC activation depends on the completion of the behavioural goal — this is consistent with sustained firing of PFC neurons — but can be interfered with by supervening goals. The SEC framework is consistent with the structure, connectivity, neurophysiology and evolution of the PFC.

Specific predictions enable the verification or invalidation of this framework (FIG. 3). For example, the theory predicts that different categories of SECs are stored in different regions of the PFC. The localization of different aspects or categories of SECs (for example, social or emotional) is based on the connectivity between specific PFC and posterior cortical (temporal–parietal) or sub-cortical (basal ganglia, hippocampus, amygdala) regions. Consistent with this, impairment of social behaviour is most evident after ventromedial PFC damage^{29,54}, whereas impairment of reflective, mechanistic behaviour is evident following dorsolateral PFC damage^{55,56}. Furthermore, neuroimaging data support the existence of dissociable networks for emotional versus non-emotional⁵⁷ and social versus non-social³⁵ SECs, and emotion-specificity of neurons in the human ventral PFC²⁶ has been shown in an electrophysiological study. The framework also predicts that online processing of an SEC would enable a person to predict subsequent events, but damage to the PFC that limited retrieval of part or all of an SEC would lead to disruption of day-to-day behaviour because individuals would have difficulty in detecting behavioural and social errors. This is supported by available evidence^{29,58,59}.

Guided activation theory

Miller and Cohen's guided activation theory proposes that the PFC stores representations of task-specific rules, attentional templates and goals⁶⁰. Essentially, the PFC 'directs' activation to bias the activation of goal-related representations that are stored in posterior cortex. This 'guided activation' of posterior representations is important in learning new rules and behaviours. Repeated activation of the same pathway creates stronger associations between them and, consequently, the role of the PFC in guiding posterior representations lessens — the role of the PFC might be virtually nil with frequently used rules or behaviours⁶⁰. Miller and Cohen compare the PFC's role to that of a switch operator determining which railway tracks a train will use — by the same analogy, if a train always uses the same track, then the switch operator is no longer necessary. Miller and Cohen propose that their theory is representational and is consistent with both the PFC's function of behavioural control and its connectivity with other brain regions. It is partially consistent with the evolutionary perspective, but is biased towards new behaviour. Furthermore, it is not explicit about how these new representations are transferred to the posterior regions that store representations of well-learned behaviours.

Miller and Cohen make specific predictions on the basis of their theory. The role of the PFC is modulatory and, therefore, it should be activated only in conjunction with posterior cortex. In addition, PFC involvement should increase as controlled processing demands increase — this is consistent with studies of cognitive control^{38,61}. The prediction that the PFC will be involved only in new behaviours is inconsistent with evidence of neural responses in the PFC to known actions^{9–11}.

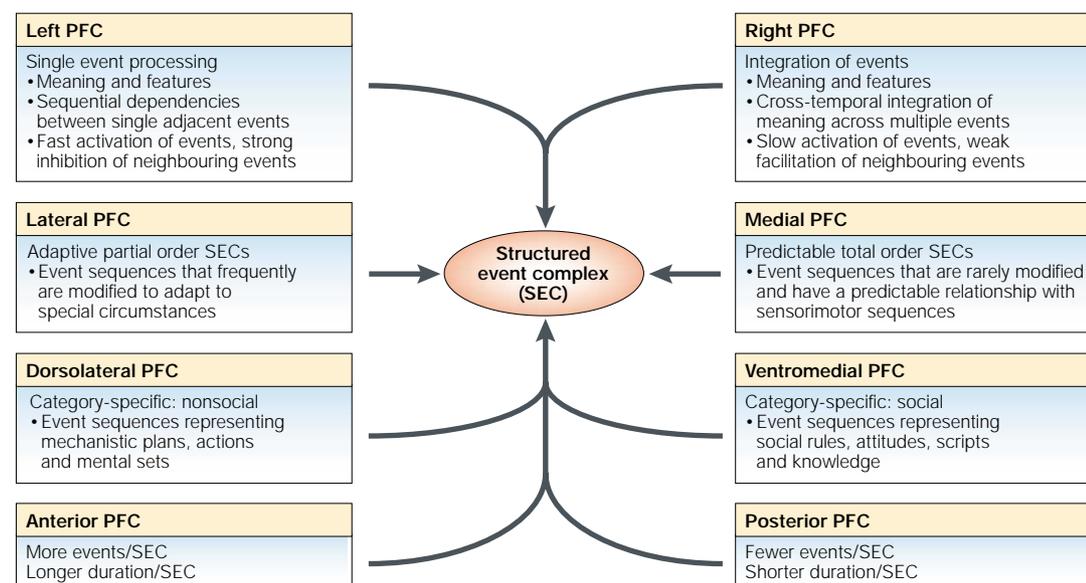


Figure 3 | The representational forms of the SEC and their proposed localization within the prefrontal cortex.

All subcomponents can contribute to the formation of an SEC, with the different subcomponents being differentially weighted in importance depending on the nature of the represented SEC and moment-by-moment behavioural demands⁵³. For example, the left anterior ventromedial prefrontal cortex (PFC) would be expected to represent a long multi-event sequence of social information with specialized processing of the meaning and features of the single events within the sequence, including the computation of their sequential dependencies and primary meaning.

Miller and Cohen claim that the PFC is important in the integration of information across stimulus domains⁶⁰. The guided activation theory also predicts that learning influences representation, organization, and hence localization. This is supported by evidence that dissociable regions are implicated in the representation of different stimulus attributes^{21,62,63}. However, this evidence seems to be inconsistent with Miller and Cohen's assertion that localization of representations in the PFC is organized in terms of broad categories with no 'modular discretely localized' forms. Rather, categories are determined by the relative strengths of competing responses with strongly asymmetric responses localized in orbitofrontal regions and symmetric/balanced responses localized in the dorsolateral PFC. There is neuropsychological^{64–67}, electrophysiological^{25,26}, and neuroimaging^{68–70} evidence that the orbitofrontal cortex, for example, is prominently implicated in social and emotional responses and behaviour. Rather than segregating the PFC on the basis of category distinctiveness, Miller and Cohen suggest that functional differences between orbitofrontal and dorsolateral PFC are, instead, due to different balances of response strength^{60,71}.

Somatic marker hypothesis

Damasio has argued that somatic markers are important in guiding behaviour^{72,73}. Somatic markers are stored memories of SOMATIC STATES that are associated with particular behavioural experiences or outcomes — this is consistent with a representational approach. Somatic markers are stored in the ventromedial PFC and enable decisions and behaviours to be selected on the basis of previous experience, even in the absence of awareness of that past experience. The ventromedial PFC is critical in the linkage of somatic markers with behavioural experience. The somatic marker hypothesis is primarily a theory of decision-making, and its neurological extent within the PFC is limited to ventromedial regions. The ventromedial PFC is described as a 'convergence zone' in which information from amygdala, hippocampus and sensory regions interacts to influence behaviour — this is consistent with a processing approach. As the somatic marker hypothesis has both processing and representational components, it is a hybrid of these approaches. The integration of information is consistent with the structure and connectivity of the PFC, although it is unclear how this viewpoint fits with the evolutionary development of the PFC as outlined earlier.

The somatic marker hypothesis predicts that damage to the ventromedial PFC will result in an impaired ability to utilize somatic markers and, consequently, in poor decision making. In addition, it predicts that emotionally charged stimuli should be associated with activation of ventromedial PFC and with somatic responses (as indexed by changes in electrodermal activity or heart rate). There is evidence consistent with these predictions from electrophysiology^{26,74,75}, neuroimaging^{70,76}, and studies of patients with ventromedial PFC damage^{64,77,78}. The somatic marker hypothesis is not intended to be a theory of PFC function in general and it would benefit from expansion to consider the

functions of other PFC regions in processing social stimuli and also how this processing interacts with or modulates the ventromedial PFC.

Temporal organization model

Fuster proposes that the PFC temporally organizes behaviour in terms of short-term memory, motor attention and the inhibitory control of interference¹⁴. He proposes mechanisms for monitoring, memory and attentional selection that prioritize goals and ensure that behavioural sequences are performed in the correct order. Temporal integration is mediated by the activity of PFC neurons and also by interactions between the PFC and posterior cortex — the specific posterior cortical areas that are involved in these interactions are determined by the modalities of the sensory and motor information. Given the emphasis on attention, short-term memory and inhibitory control, the model seems to be a processing viewpoint. However, Fuster also describes PFC function in terms of 'motor memory' (schemas), with a hierarchy of motor representations within the PFC. Attention and working memory are properties of the representations (neural networks), rather than explicit 'processes' in terms of computational procedures. Fuster's model is a hybrid of the representational and processing approaches and is consistent with the evolution and neurophysiology of the PFC. Motor memories that are stored in the PFC become more complex or abstract as the region becomes more anterior. Fuster proposes that the functions of the ventromedial PFC parallel those of the dorsolateral PFC, but with the addition of emotional information, given the connectivity between ventromedial PFC and limbic regions (such as the amygdala).

Fuster believes that automatic actions are stored in the basal ganglia and premotor cortex, with PFC representation reserved for actions or behaviours that are not habitual or well learned. Consistent with this viewpoint, the premotor cortex and basal ganglia are known to be important in movement preparation^{79–81}; however, the PFC has been implicated in both novel and well learned tasks^{36,82}. Decision-making is the result of integration of memorial, experiential, affective and motivational inputs that select the response after the resolution of competition between the available information. Thus, Fuster suggests that decision-making should be associated with networks involving anterior PFC (complex behaviour), medial temporal (memory) and limbic (affect and motivation) regions. Neuroimaging studies have implicated prefrontal–parietal^{83,84}, prefrontal–cingulate^{84,85} and orbitofrontal–limbic⁶⁶ networks in decision-making. Clearly, the evidence is mixed with respect to the neuroanatomy of decision-making, which might be partly due to the heterogeneity of the decision-making tasks used in these studies. Finally, Fuster suggests that inhibitory control of interference, irrespective of its source, is performed by orbitomedial PFC neurons. Although there is evidence consistent with a role for orbital PFC in inhibition^{86–88}, there is also evidence consistent with networks including the dorsolateral PFC and anterior cingulate being important in inhibition^{38,89–93}.

SOMATIC STATES
Emotional state as indicated by
musculoskeletal and visceral
(body) states.

Table 1 | Theories of prefrontal cortex function and the extent to which each meets our criteria

| Theory | Type | Biology | Testable | Supported | Evolution |
|---------------------------|------------------|----------|----------------------|----------------------|-----------|
| Adaptive coding | Processing | Partial* | Yes | Partial [§] | Unclear |
| Attentional control | Processing | Partial* | No | Partial [§] | No |
| Connectionist | Representational | Yes | Partial [‡] | Yes | Yes |
| Structured event complex | Representational | Yes | Yes | Yes | Yes |
| Guided activation | Representational | Yes | Yes | Partial [§] | Partial |
| Somatic marker hypothesis | Hybrid | Yes | Yes | Yes | Unclear |
| Temporal organization | Hybrid | Yes | Yes | Partial [§] | Yes |
| Working memory | Hybrid | Yes | Yes | Partial [§] | Unclear |

Biology: is the theory consistent with the structure, connectivity, and neurophysiology of the prefrontal cortex (PFC)? *The theory is not consistent with all of these. Testable: does the theory make predictions that enable its verification and invalidation? †The theory makes some predictions but is insufficiently specified to enable detailed hypothesis testing. Supported: are there neuropsychological, electrophysiological, and neuroimaging data that support the theory? §Data exist that are consistent and inconsistent with the theory. Evolution: is the theory consistent with what we know of the PFC's evolutionary development?

Working memory model

Goldman-Rakic suggests that the PFC serves as a working memory structure that keeps stimulus representations active for short periods of time^{15,94}. Her model is primarily based on neuropsychological and electrophysiological research in nonhuman primates, but she proposes that it also applies to humans. The PFC is part of an integrated network of regions — temporal, parietal, premotor and limbic — that is involved in the representation of stimuli in their absence; this enables behaviour to be guided by internal representations rather than relying on the presence of external stimuli. Goldman-Rakic further proposes that the other brain regions (such as the brainstem) modulate the PFC. Her model focuses primarily on dorsolateral PFC function, with the orbitofrontal cortex implicated in behavioural regulation by maintenance of the internal representations of external stimuli. However, the model does not detail what this regulation entails, other than to state that accessibility of central representations of reward and punishment is important. The working memory model is a hybrid of the processing and representational approaches and is consistent with the structure, connectivity and neurophysiology of the PFC. It is unclear how the model fits in with the evolutionary perspective outlined earlier.

The model states that the disruption of behavioural regulation by internal representations of the stimuli will lead to distractibility and perseveration. These problems have been consistently reported in patients with damage to the PFC^{95,96} and in primates with PFC lesions⁹⁷. Goldman-Rakic notes that a variety of tasks should demonstrate impairments in individuals with immature (young children) or damaged PFC — including problems in selective attention^{98,99}, response conflict^{100,101}, processing of temporal order^{31,32}, planning^{102–104}, decomposition of a task into goals and sub-goals^{45,103} and generation of new or unusual responses¹⁰⁵. These tasks all require symbolic representations of stimuli to be maintained 'on-line' in the absence of the stimuli themselves. The evidence generally supports this position. However, there is also some evidence that selective attention might be intact after PFC damage¹⁰⁶.

Goldman-Rakic proposes that different domains of knowledge representation might be localized to

dissociable regions of the PFC. Although the model states that spatial representations might be localized to area 46, it does not specify how these representations differ from spatial representations stored in, for example, parietal cortex, where other types of knowledge are stored, nor how these domains are integrated. Inconsistent neuropsychological evidence, taken together with its topographical limitation to dorsolateral PFC, makes the working memory model an incomplete model of PFC function.

Summary and conclusions

The aim of this review was to consider the state and range of processing and representational models of PFC function. We began by proposing five criteria that could be used to judge a theory's ability to provide a rational account of PFC function. The extent to which we believe the models outlined above meet our criteria is summarized in TABLE 1.

In terms of specific approaches, the models meet our criteria to varying degrees. Those with some claim of representation are consistent with the neurophysiology, connectivity and structure of the PFC, thus providing support for the usefulness of the representational approach to understanding PFC function. Most models provide specific predictions that enable the testing of their position; however, the specificity of the predictions varies between models. Although all the models are supported to some extent by the available cognitive neuroscience data, it is not the case that each model addresses all of the available data. For example, the somatic marker hypothesis addresses some potential functions of the ventromedial PFC, but is not intended to address any data regarding dorsolateral PFC function and thus is not inconsistent with these data. Finally, there is variability in the degree to which the models meet the evolutionary criterion. With respect to specific theories, without modification, no single theory of PFC function appears to explain all of the available data.

In terms of general approaches, the representational approach seems to be most consistent with the neurophysiology, structure, and connectivity of the PFC — either with or without processing components. In addition, a representational approach is consistent with

ASSOCIATIVE STRENGTH
The degree to which different representations are associated.

a modern cognitive neuroscience view of how the brain stores aspects of certain kinds of stimuli (for example, words or objects) in posterior cortex. The representational approach forces the investigator to describe the features of the representation — such as age when representation was first acquired, how often it is activated, and its ASSOCIATIVE STRENGTH to other representations — and, by default, enables specific hypotheses to be tested. This enables identification of the properties that influence knowledge storage and retrieval in the normal brain. In addition, a representational approach makes simple predictions about the effects of brain damage on the retrievability of representational knowledge. We believe that the pure processing approaches are inconsistent with the neurophysiology, structure, connectivity and evolution of the PFC, and that adoption of a representational approach to understanding PFC function will prove fruitful. The representational approach does not eliminate the use of the term 'process' to describe activation states in the PFC. In the representational approach, 'processes' in cognition are a set of representations that, when activated,

remain activated over a period of time. For example, in this view, working memory is simply the activation of a set of representations over a limited time period. The time period itself reflects either the actual time required for the representational action to be completed, or the time it takes for a compressed version of the representational action to be completed (for example, to recite a verbal description of a plan executed in real time). Given this definition, we predict that local computational procedures for representations are required to determine and enhance the relationship of one representation to others in the local (and distant) networks, to sustain the activated representation(s), and to refine the form of the representational memory itself over time. Given that a revolutionary explanation about how and why the human PFC would support only temporary processes without a knowledge base has not been offered by any of the process modellers, we think that the most parsimonious approach to understanding its role in human behaviour is to explore and examine the nature of knowledge stored as representations in the PFC.

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