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Contrasting network and modular perspectives on inhibitory control

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A prominent theory proposes that the right inferior frontal cortex of the human brain houses a dedicated region for motor response inhibition. However, there is growing evidence to support the view that this inhibitory control hypothesis is incorrect. Here, we discuss evidence in favour of our alternative hypothesis, which states that response inhibition is one example of a broader class of control processes that are supported by the same set of frontoparietal networks. These domain-general networks exert control by modulating local lateral inhibition processes, which occur ubiquitously throughout the cortex. We propose that to fully understand the neural basis of behavioural control requires a more holistic approach that considers how common network mechanisms support diverse cognitive processes.

Modular versus network approaches to understanding cognition

A major focus of contemporary neuroscience has been to map the functional architecture of the human brain by localising distinct cognitive processes to dedicated brain regions and their connection pathways. In the case of cognitive control, this modular approach has generated valuable markers for clinical research and assessment; however, *en masse* the resultant theoretical models are problematic because they often assign putatively distinct cognitive processes to the same brain regions. Furthermore, they distract from the role of more widespread functional networks in cognition. This problem is particularly notable for domain-general brain regions, which activate in a coordinated manner during the performance of a variety of cognitive tasks. The ongoing debate regarding the neural mechanisms that underpin motor response inhibition is a prominent example of this issue.

The inhibitory control hypothesis

Response inhibition refers to the process by which routine, initiated, or otherwise prepotent motor actions are effortfully withheld or cancelled. Classic paradigms such as the Stop-Signal Task (SST; see Glossary) [1] and Go/No-Go Task (GNG) are used to investigate the neural mechanisms of response inhibition in healthy individuals and to assess disinhibition in disease states. Quantitatively, the performance of response inhibition tasks can be modelled as a horserace, in which Go and Stop processes compete to determine behaviour [2–4]. Traditional approaches to functional–anatomical mapping have provided evidence that the right inferior frontal gyrus (rIFG) and anterior insula (aIns) are critically involved in response inhibition tasks. For example, neuroimaging has shown increased activation in the rIFG/aIns when routine responses are cancelled during the SST [5,6]. Activation in these regions is abnormal in disease states that are characterised by disinhibition [7–10]. Similarly, acquired damage within the rIFG/aIns is associated with poor SST performance [11] (Box 1). On the basis of these results the inhibitory control hypothesis has been proposed (Figure 1A), which states that 'a specific executive function, response inhibition, can be localized to a discrete region of the PFC [prefrontal cortex]' [11,12] and that 'inhibition is localized to the rIFG alone' [12]. When infrequent, salient, or surprising stimuli are detected the inhibition module is proposed to rapidly activate the subthalamic nucleus (STN) via a hyperdirect pathway. The STN then inhibits ongoing motor processes [13–16]. A recently revised version of this hypothesis emphasises that these brain regions form a network; however, it continues to assert that the rIFG area is specialised for the implementation of inhibitory control [17]. This is a modular view because it proposes that a specific brain region and its connection pathways support a discrete cognitive function.

Glossary

Default mode network (DMN): is a set of brain regions that tend to activate together when an individual is either at rest or performing a routine task.
Go/No-Go Task (GNG): is a paradigm that is used to measure motor response inhibition. It involves omitting a routine response.
Independent component analysis (ICA): is a data-driven method for blind source localisation, that is, it may be used to estimate source signals from mixtures of those signals without ever being exposed to the sources individually. When applied to neuroimaging data, ICA generates spatial maps that may be interpreted as networks because they capture statistical dependencies of regional brain activations across time. It also outputs a time course for each component, which may be interpreted as the level to which each network is activated at each point in time.
Multiple demand cortex (MDC): is a set of brain regions that are activated across a particularly broad range of task contexts. It should not be considered a network as such, because the method that was used to define it did not include any analysis of connectivity across brain regions; therefore, it may consist of multiple distinct networks.
Stop-Signal Task (SST): is a cognitive paradigm that is commonly used to measure motor inhibition. It involves the cancellation of an initiated response.

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Box 1. Inhibitory control in disease

Understanding the neural basis of inhibitory control is an important clinical challenge because patients with a wide range of pathologies show disinhibited behaviour. Motor inhibition has been extensively studied clinically using paradigms such as the Stop-Signal Task and Go/No-Go Task, which have proven to be valuable tools for identifying the pathophysiological correlates of abnormal behaviour. Impairments in inhibition have often been associated with rIFG/aIns abnormalities. For example, patients with frontotemporal dementia show impairments associated with abnormalities in the structure and function of this region [8,9], and the activation of this region is sometimes attenuated in patients with behavioural disinhibition, the most prominent examples being attention deficit hyperactivity disorder (ADHD) and addictions [9]. Drugs that are used to treat ADHD also modulate rIFG/aIns activation levels [7], and focal lesions that involve the rIFG and surrounding structures are associated with impairments in SST performance [11], which can be part of a disabling dysexecutive syndrome [28]. In addition, the presence of traumatic axonal injury to the white matter connections of rIFG/aIns is a key cause to behavioural problems [73]. Following traumatic brain injury (TBI), impairments of response inhibition are correlated with damage to the connections of the cingulo-opercular network (salience network), and this damage predicts a failure to control linked activity that usually accompanies increased cognitive control [10]. These results suggest a causal influence of the cingulo-opercular network on other networks such as the DMN when increased cognitive control is required, and also illustrate the value of quantifying network interactions when defining the neural basis of cognitive control.

Response inhibition paradigms provide important markers for clinical research and assessment. However, the inhibitory control hypothesis is controversial. Several researchers have argued that the attempt to map a discrete inhibitory ability onto a dedicated brain region is misguided [18–26]. Here, we review evidence in support of our alternative hypothesis, which states that common neural mechanisms of domain-general frontoparietal networks underlie a variety of cognitive control processes, with response inhibition being one important example.

Is motor response inhibition a valid behavioural construct?

It remains unclear whether inhibition is a discrete aspect of human cognition. For example, models of frontal lobe function based on neuropsychological evidence often do not include inhibition as an explanatory phenomenon [27,28]. Furthermore, there is limited psychometric evidence to support the assumption that response inhibition is a discrete cognitive construct [29], although see [30,31]. Performances of tasks that require inhibition tend not to correlate strongly with each other [32] unless the tasks are very similar [33], indicating that that they depend on different abilities [34]. Relatedly, a wide range of

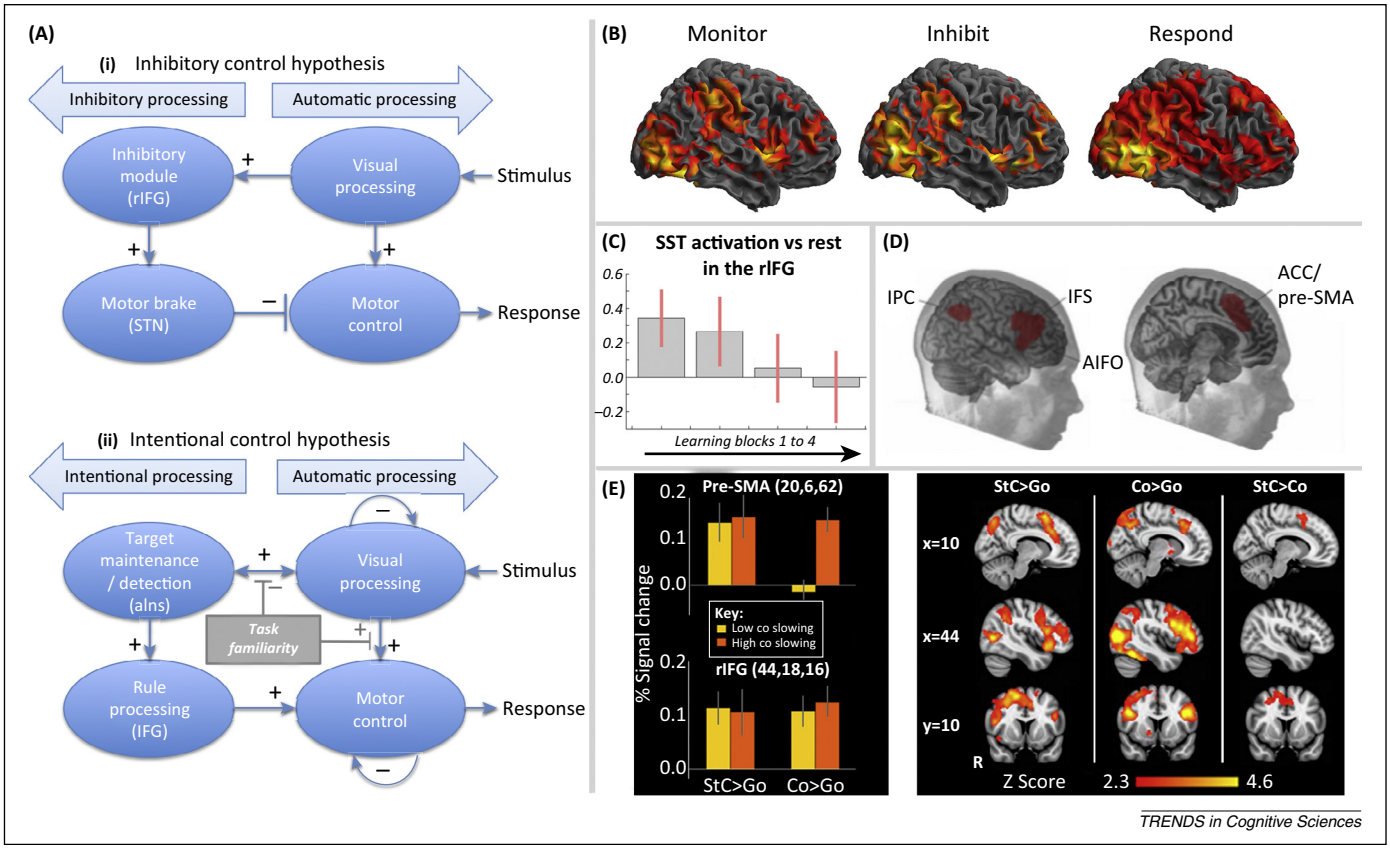

Figure 1. Theoretical models and empirical findings. **(A)** Alternative models of right inferior frontal gyrus/anterior insula (rIFG/aIns) function. (i) Inhibitory control hypothesis. (ii) Intentional processing hypothesis [41]. **(B)** The inhibition condition of the classic Stop-Signal Task (SST; centre) activates a set of brain regions including much of the rIFG [18]. Activation tends to be strongest within a network including the right aIns/inferior frontal operculum and anterior cingulate cortex. Similar activations are observed during other conditions including when targets are passively monitored (left) or elicit a planned motor response (right). **(C)** Task-related activation throughout the rIFG/aIns volume attenuates sharply as the SST becomes more familiar [18]. **(D)** A set of brain regions is commonly recruited under a very broad range of cognitive conditions, indicating general involvement in cognition [43]. Multiple-demand cortex (MDC) includes the anterior insula/inferior frontal operculum (AIFO), the inferior frontal sulcus (IFS), anterior cingulate cortex and pre-supplementary motor area (ACC/pre-SMA), and inferior parietal cortex (IPC). It overlaps heavily with the rIFG/aIns. **(E)** The presentation of 'Continue' trials that do not require stopping (Co) and the presentation of stop trials (StC) are both associated with rIFG/aIns activation (right). The contrast between stopping and continuing shows specific activation in the pre-supplementary motor area rather than the rIFG/aIns, which is unrelated to whether slowing is observed on subsequent trials (low and high Co trial slowing) [23].

Box 2. Functional anatomy of the inferior frontal gyrus and anterior insula

A fundamental question regards how the rIFG/aIns volume is organised into functionally distinct subregions. One approach to this question is to identify voxels with similar activation time courses using model-free methods, a popular example being spatial independent component analysis (ICA). This multivariate method has been used to define intrinsic connectivity networks based on common patterns of neural activity [74] and can be used to identify distinct response profiles in an unbiased way, which can then be investigated in terms of their local activity and their interactions with other brain regions [18,75,76]. The application of ICA in three separate studies of response inhibition provided a consistent functional parcellation of the rIFG/aIns [18,19,41]. Subregions within the rIFG/aIns were each associated with a distinct functional network, the other regions of which responded to similar task demands (Figure I). Importantly, although all of the ICA regions coactivated during response inhibition, no voxel or region activated to inhibition demands specifically. Furthermore, the ICA subregions were dissociable from each other by their responses to other cognitive conditions [41]. For example, the aIns and frontal operculum showed strong activation to targets in all conditions, including when they cued the immediate execution of a motor response (Respond), the planning of a future motor response (Prepare), the incrementing of an internal count (Count), or even when they were passively monitored and cued no further process at all. By contrast, the pars opercularis did not activate when targets were passively monitored, but did in the other three conditions, where the targets cued some further task-related process. Conversely, the mid-insula only responded when a motor response was being executed. On the basis of results of a meta-analysis [77], it has been proposed that the most dorsal and anterior extent of the rIFG, indicated by the green crosshair in Figure IB, houses the response inhibition module [16,17]. However, the proposed coordinates overlap with a point in the brain where several ICA subregions intersect, a relationship that was consistent across all three studies and at multiple levels of ICA dimensionality. These results highlight the limitations of the meta-analysis approach when seeking to map a heterogeneous cognitive construct such as response inhibition.

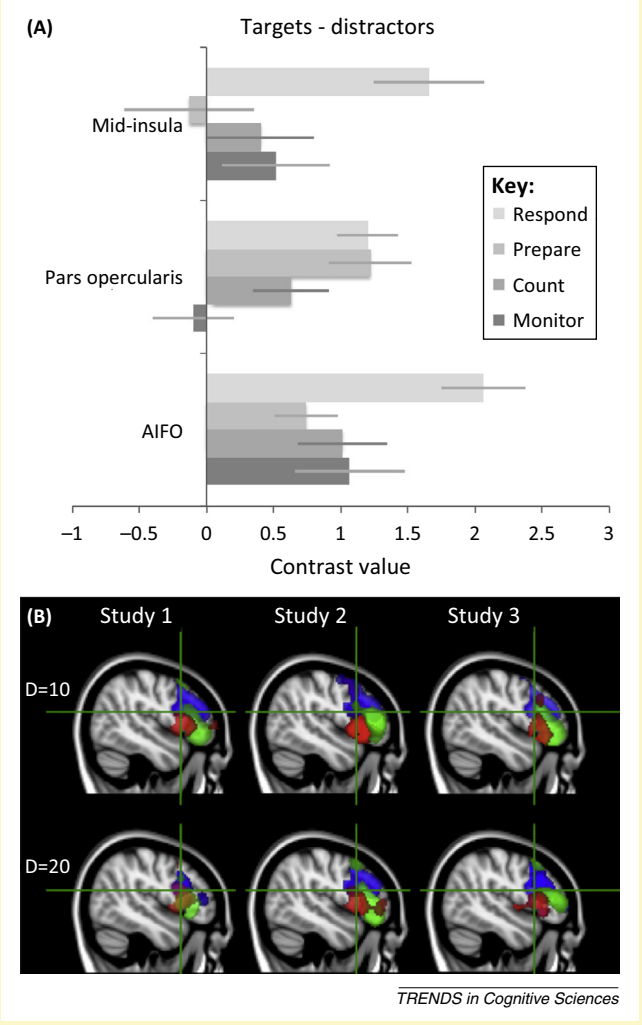

Figure I. Neuroimaging findings. **(A)** Activations during different cognitive conditions within ICA-derived regions of interest [41]. **(B)** Rendering of the ICA component maps that are most proximal to the proposed coordinates (green crosshairs) of the inhibition module. Abbreviation: ICA, independent component analysis. Reprinted under creative commons licence (https://creativecommons.org/licenses/by-nc-nd/4.0/).

neuropsychological data, including classic inhibitory paradigms such as the Stroop Task [35], can be explained without inclusion of a discrete response inhibition ability [28]. Indeed, it has been claimed that individual differences in the speed of perceptual and motor processing are sufficient to account for response inhibition task performances [36]. Thus, although disinhibition is an important symptom in a range of clinical populations, it remains to be determined whether it is distinct from other aspects of cognition and it is unlikely to be unitary in nature. Consequently, it is difficult to justify the search for a unitary inhibitory processing module.

Is there evidence for a response inhibition module?

The neuroimaging evidence for a dedicated inhibition module is also unconvincing. Studies that have sought to localise the inhibition module typically assume that brain activation during the cancellation of a routine action must reflect a neural inhibition process. Some studies have reported heightened activation in the rIFG/aIns during successful versus unsuccessful Stop trials [6,37]. This could be taken as evidence for a specific inhibition process; however, it could also be a consequence of transient lapses in attention causing slowed intentional processing of stop cues. Indeed, activation within this region is unlikely to be directly contingent on successful inhibition, as other studies with similar designs have reported the opposite pattern of results [18,19,38,39].

More commonly, studies of the SST contrast event-related activities during Stop minus Go trials, which generates very reliable rIFG/aIns activity. However, response inhibition tasks rarely control for other confounding cognitive demands; consequently, the observation of regional activation can be interpreted in different ways. In fact, many studies have reported rIFG/aIns activity during tasks that have no overt response inhibition demands [24]. For example, a recent series of studies used novel variants of the SST to vary motor inhibition demands while controlling for attention [18,19,40,41] (Figure 1B, Box 2). Although the rIFG/aIns was activated on Stop trials, similar levels of activation were evident during blocks in which the same Stop stimuli were simply monitored, cued the execution of a planned motor response, or cued the incrementing of an internal count [18,19,41]. In a parallel study, the attentional demands on Stop trials were controlled for using a Continue condition, in which an additional

infrequent stimulus signalled that there would be no need to cancel the initiated response [23] (Figure 1E). The Stop and Continue stimuli generated similar activation throughout the rIFG/aIns region. These findings indicate that functional activations during the SST do not relate to response inhibition demands *per se*.

Proponents of the response inhibition hypothesis have claimed that the control conditions from these studies must have hidden inhibitory demands. They propose that any stimulus that is surprising, salient, or infrequent will recruit inhibition [17]. However, this is not a convincing argument. It is unlikely that the presentation of a Target or a Stop stimulus is surprising in these studies, as these events occur on approximately a quarter of trials and the participant has the explicit intention of detecting them. Furthermore, the perceptual salience of Go and Stop signals are usually well matched, for example, a vertically as opposed to horizontally oriented arrow [6,18,19]. More broadly, it has been reported that significantly greater rIFG/aIns activation is evident during presentation of target stimuli, even when the frequency and salience of targets and distractors are precisely balanced [42]. It should also be noted that behaviourally, increased rIFG/aIns activity is not always accompanied by slowed motor responses (Figure 1E). For example, in one study, there was no significant slowing of routine responses when Stop stimuli were simply monitored, yet rIFG/aIns activation was as strong as during the Stop trials of the SST [18]. In another study, rIFG/aIns activity during 'Continue' trials was evident regardless of whether or not small amounts of slowing were present [23]. This is problematic for the inhibitory control theory, because if hidden inhibitory processes can be reverse inferred for any task that activates the putative inhibition module, regardless of whether there is a relationship with motor slowing, then they would be too general to warrant being labelled motor response inhibition and abstracted to an extent that would effectively be unfalsifiable [22]. Indeed, the slowing of responses during attentional orienting is not proof that an inhibition module has been engaged because common attentional mechanisms can account for the same phenomena without recourse to a dedicated inhibition process (Figure 1A). Thus, when taking a broader view, the results indicate that the rIFG/aIns has a more general task-oriented role in cognition [19,26,43].

Globalist accounts of cognitive control

A simpler explanation for the experimental findings is that there is no response inhibition module; instead, the rIFG/aIns houses components of a more general processing resource (Figure 1D). Globalist models propose that some regions of cortex are domain general [44,45], that is, they rapidly adapt to support a variety of novel [18,46] or demanding [44,47] tasks. Cortical regions showing this type of flexibility have been variously referred to as multiple-demand cortex (MDC) [43,48], the cognitive control system [49], or the task-activation ensemble [50]. Electrophysiological research has provided strong evidence of this flexible processing [51]. Cell recording studies in non-human primates demonstrate that the same MDC neurons code selectivity for one or other dimension of a task depending on the current conditions [52]. These neurons can switch from coding for one aspect of a multistage task to another in a fraction of a second and have the capacity to maintain preparatory information in stable low-activity states [53]. MDC includes the rIFG/aIns; conversely, the wider set of brain regions recruited during response inhibition tasks corresponds closely to MDC [18]. Consequently, the most parsimonious explanation of the experimental findings is that response inhibition during the SST is one example of the broad class of intentional processes that are supported by domain-general systems (Box 3).

Inhibitory control as an emergent property of biased local competition

It is important to distinguish between inhibition at the level of local neural populations, large-scale brain systems, and overt behaviours. We propose that behavioural inhibition is an emergent property of common neural mechanisms that are ubiquitous throughout systems in the human brain: specifically, local lateral inhibition and top-down potentiation [54,55] (Figure 1A). Our alternative

Box 3. A network-based taxonomy for cognitive control

The controversy about how to map the neural correlates of response inhibition illustrates the more general issue of how best to define the fundamental components of human cognition. Terms such as inhibition, working memory, attention, and executive function describe important aspects of cognition that appear to be qualitatively distinct. Consequently, they are often assumed to relate to different neural systems and separate lines of research have sought to map them onto the brain. However, tasks that are designed to probe these aspects of cognition tend to activate the same functional networks. Furthermore, contrasting different conditions of tasks from within any one of these domains reliably dissociates those same networks. Therefore, the intuitive constructs that have historically constituted our taxonomy of human cognition appear largely orthogonal to the underlying functional organisation of the brain. An alternative approach is to categorise cognitive processes based on their relationship with functional networks. Indeed, several studies have reported that, unlike psychometric factors, the functional networks observed within MDC are very consistent across diverse cognitive tasks [18,76,78,79]. They are evident when examining differences in task contrasts, but also when examining fluctuations in activation across time, even at rest. This research has precipitated a transition towards network-centric models of brain organisation [80–82] and has provided a framework that is already proving useful for understanding pathological brain dynamics [83–86]. Nonetheless, the potential of this approach is still largely untapped. Specifically, studies that have sought to classify cognitive tasks based on network activations have primarily focused on providing theoretical interpretations of the processes that underlie those classes; they have not tested the relevance of those interpretations to the organisation of human cognitive abilities. We argue, that to realise the full potential of this approach, it will be necessary to go further and confirm the behavioural construct validity of the network-derived cognitive constructs. In a recent article, a preliminary attempt was made to achieve this in the context networks that overlap heavily with MDC, which is associated with the general intelligence construct 'g' [76]. The results showed that although these networks often coactivated they were clearly dissociable with regard to the cognitive tasks that they responded most strongly to. Furthermore, the levels to which tasks activated these networks provided a good prediction of the cross-correlations observed when analysing performance data from a large ($n = 44\,600$) behavioural cohort. This study supported the view that prominent components of human cognitive ability reflect the manner in which the frontoparietal cortices are organised into functional networks.

model explains the intentional control of motor actions as an interaction between a top-down signal originating in MDC and local populations of neurons coding for competing representations [56] at multiple levels of sensory and motor circuits [3,4]. Routine motor responses to visual stimuli are supported via direct connections from visual to motor processing brain regions. Nonroutine tasks additionally involve MDC, which codes a temporary program for performing nonautomated aspects of behaviour. MDC outputs top-down signals, which potentiate task-relevant processes in visual and motor areas. Competing processes, including routine motor responses, are then downregulated via local inhibitory connections.

Many characteristics of inhibitory behaviour can be accounted for by this simple mechanism [2–4]. In the case of the SST, when a Stop trial is expected, MDC neurons enter a stable and low-activation preparatory state [53] leading to the upregulation of representations within sensorimotor areas that are relevant to the Stop process. This top-down potentiation has the secondary effect of influencing competing processes by lateral inhibition, thereby producing a slowing of routine responses. When a Stop stimulus is detected, there is heightened activity in MDC [18,53,57] and sensorimotor areas [18,57]. The increased potentiation of representations that are relevant to the Stop process further slows or halts routine processes by lateral inhibition, thereby producing the stopping behaviour. A major advantage of this model is that it can readily account for the broader range of cognitive demands that engage the rIFG/aIns.

There are computational reasons to favour top-down control via a potentiating signal. A specific top-down inhibitory system would be an inefficient use of resources. Consider monitoring a sequence of targets in a noisy scene where distracting stimuli constantly change. To prevent task processes from being disrupted, any source of top-down inhibition would have to represent and downregulate each distracting item individually. Sensory inputs would have to be scanned to identify new distractors and the representation of distractor items would have to be continually maintained, monitored, and updated. As the number or rate of distractors increased, such a system would reach capacity and fail. By contrast, the source of a top-down potentiating signal could represent, process, and potentiate just those items that were relevant to the current task. Local competition within sensory processing streams would efficiently work to downregulate all competing distractors in parallel. Given the computational advantages of top-down potentiation, it is unsurprising that electrophysiology research has provided a wealth of evidence demonstrating that frontal cortex neurons represents task-relevant inputs, rules, and responses [51–55,58,59].

Animal studies of motor control

Notably, our alternative model is highly compatible with the extensive body of non-human primate and rodent research investigating the involvement of motor circuits in response preparation and inhibition [3,4,60]. These studies have reported that the frontal eye fields, superior colliculus, and pre-supplementary motor area all contain neural populations that show distinct responses to Go and Stop trials during countermanding tasks [4]. Some neurons increase activity after the Go stimulus. They rapidly decrease activity after the Stop stimulus, but only on successful inhibition trials. Other neurons decrease activity after the Go stimulus and increase activity sharply after the Stop stimulus. This line of research has also demonstrated that the supplementary motor and pre-supplementary motor areas are involved in the proactive control of motor responses [61,62] and contribute with the anterior cingulate cortex to error monitoring and executive control during countermanding tasks [63,64].

Elegant computational modelling has demonstrated that locally competing Go and Stop processes provide the best explanation of the neural profiles observed within the motor circuits during response inhibition and can account for horserace behavioural dynamics [3,4]. We argue that response inhibition is an emergent property of top-down potentiating signals, which have their origin with MDC, biasing competition between these Go and Stop neural populations. Local competition is likely to be occurring in parallel at multiple stages of sensory [36] and motor processing [3,4], and within an actively maintained MDC task program. Therefore, biasing competition towards representations that are relevant to the Stop process at any one of these stages could contribute to the downregulation and slowing of routine responses. From this perspective, response inhibition is an emergent property of ubiquitous neural mechanisms as opposed to a specific module and its connection pathways.

A multiple systems perspective on response inhibition

On the surface, the results from the animal electrophysiology research might appear at odds with those from the human neuroimaging and neuropsychological literature. Specifically, the former has demonstrated that response inhibition can be entirely accounted for by local processes within motor circuits, whereas the latter has highlighted a critical role for the rIFG/aIns. However, it should be noted that for an animal to perform an inhibition task, it is necessary to apply lengthy training with reinforcement protocols. By contrast, humans are typically studied after minimal instruction and practice. This difference is important, because MDC is very sensitive to the novelty of cognitive tasks. For example, SST-related activity within MDC attenuates rapidly during the timescale of an fMRI scan session (Figure 1C), with the task primarily activating sensory and motor regions once it has been learnt [18]. Similar effects have been reported during target detection tasks [46] and when arbitrary stimulus–response mappings are being learnt by repetition [65,66]. These results demonstrate that tasks such as the SST are supported by different brain systems at different stages of learning. A likely explanation for this phenomenon is that when the SST is novel, substantial intentional processing is initially needed to support the arbitrary stimulus–response mappings that constitute the task program. This intentional processing is provided by MDC. As the task is repeated over many trials, more direct mappings between the stimulus and response representations are established. At this stage, the activations and interactions of

the Go- and Stop-related representations within sensory and motor brain regions become sufficient to support the task [41]. From this perspective, the combination of functional networks that support performance of the SST depends on the type of motor response that is being countermanded [4] and the shifting balance between intentional and routine processing that occurs with learning [18,65,66]. Therefore, a novel prediction of our model is that horserace dynamics should characterise response inhibition psychophysics across a variety of inhibition task contexts and at all learning stages, because they are an emergent property of neural mechanisms that are common across diverse functional networks; however, the exact parameters of the model [e.g., Stop-Signal Reaction Time (SSRT)] will vary across tasks and learning stages because they engage different networks.

Do anticorrelations between functional networks reflect top-down inhibition?

Anticorrelations between remote brain regions might be taken as evidence of long-range inhibitory interactions but this is unlikely to be the case. For example, the lateral frontal cortex activation observed during response inhibition tasks is typically observed in conjunction with reduced activation within the default mode network (DMN) [67]. One interpretation of this anticorrelation is that DMN activity might be actively downregulated by an inhibitory module within the rIFG/aIns. However, this pattern of activity can be produced without the need for a top-down inhibitory signal [68,69]. For example, coarse-grained models that simulate whole-brain dynamic interactions between brain regions show that anticorrelated activity in patterns that resemble intrinsic connectivity networks such as the DMN can be produced by excitatory connections alone when they are constrained by the known structure of white matter tracts. This is observed for interactions in resting state [69] and when simple behaviour is modelled [68], a result that implies that structural connectivity within the brain is organised in a way that allows network control (i.e., coordinated task-specific fluctuations) to emerge without the need for top-down inhibitory signals.

Network dynamics during cognitive control

Although MDC is recruited *en masse* during response inhibition paradigms such as the SST, there is clear evidence for functional heterogeneity [40,57,70–72]. Therefore, a major challenge is to determine how MDC networks differ from each other (Box 3) and how they coordinate to support response inhibition and cognitive control. Results using functional connectivity analyses are not compatible with the notion of an inhibition-dedicated frontal lobe region. More specifically, several distinct functional areas can be identified within the rIFG/aIns (Box 2). All of these areas respond to response inhibition demands. Heightened connectivity is observed between rIFG/aIns and the STN during response inhibition; however, similar effects are evident for a range of control conditions, including when infrequent motor responses are executed as opposed to routine responses cancelled [18]. Furthermore, statistically significant (and more robust) effects are evident throughout the entire graph of frontoparietal network connections (Figure 1E). Notably, individual differences in SST performance correlate with connectivity measures taken throughout that graph as opposed to any specific connection pathway. These results demonstrate that the notion of a hyperdirect pathway is overspecified both functionally and anatomically. The most parsimonious explanation for these results is that the ability to perform motor response inhibition tasks relates to interactions that occur across multiple domain-general networks (Box 3), each of which makes a broad contribution to cognition.

Box 4. Outstanding questions

- Is there a definitive mapping of the large-scale networks that are involved in cognitive control? Are the same networks consistently present when applying data-driven and model-free analyses to data from a variety of task contexts and when using different analysis methods? If so, what are their spatial topographies, how do they differ across individuals and how does this relate to individual differences in cognition?
- What is the specific functional role of each network? To address this question, it may be optimal to analyse results from the broader published literature to eschew the problem of inferring overspecified functions for domain-general systems. However, a challenge will be to achieve this without bias from the inherent assumptions of the literature regarding precisely what comprises the distinct components of human cognition.
- Do the distinct components of human cognitive ability have their bases in different functional brain networks? This question could be addressed in part by testing whether task network loadings predict individual differences in performance, and in part by testing whether inferred network functions predict the relationship between pathological interindividual differences in cognitive ability and network abnormalities.
- What is the basis of the relationship between functional network mechanisms and cognitive processes? To address this question network dynamics must be examined in finer detail. This could be achieved by combining high spatial resolution fMRI with high temporal resolution electroencephalography (EEG) data. Specifically, it would be informative to investigate whether putatively distinct cognitive control demands modulate: (i) different inferior frontal networks, (ii) distinct parameters of the same inferior frontal networks, or (iii) the same inferior frontal network parameters.
- How are the same neural networks able to support such apparently disparate cognitive processes? To answer this question, it will be necessary to go beyond static functional anatomical mappings or cognitive flow charts. Instead, multimodal findings must be combined into a coherent theoretical model instantiated as a working simulation. To be plausible, this model must also capture the non-static relationship that is observed between network dynamics and cognitive behaviours, for example, by applying plasticity mechanisms to progressively shift the balance between routine and intentional processing pathways when a task is being learnt.

Concluding remarks

Response inhibition tasks such as the SST provide sensitive and valuable proxy measures of cognitive control ability. However, there is no convincing evidence for a specialised inhibitory module. We propose that response inhibition is one prominent example of a broader class of cognitive control processes. These processes are likely to be emergent properties of the interactions of domain-general networks (Box 4). 'Inhibition' between neurons occurs ubiquitously across the brain at the local level, which in combination with a top-down potentiation signal from MDC is sufficient to explain many forms of cognitive control including motor response inhibition.

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