

Multiple conflict-driven control mechanisms in the human brain

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Conflict between competing neural representations is thought to serve as an internal signal for the recruitment of 'cognitive control', which resolves conflict by biasing information processing in line with current task demands. Because conflict can occur at different levels of stimulus and response representations, several recent investigations have examined whether conflict-driven cognitive control is domain-general or domain-specific, that is, whether control recruited by one type of conflict affects the resolution of another, but these studies have produced contrary conclusions. I argue here that a critical reading of this literature indicates that the effects of conflict-driven control are domain-specific and are probably mediated by multiple, independent conflict-control loops that can operate in parallel.

Introduction

'Cognitive control' describes the ability to generate, maintain and adjust sets of goal-directed processing strategies (task sets). One central question for theories of cognitive control is how the need for reinforcements or adjustments in task sets is determined. The influential 'conflict-monitoring model' [1] proposes that this function could be served by an evaluative mechanism monitoring for internal processing 'conflict', reflected in the simultaneous activation of mutually incompatible representations in the brain. Specifically, the model describes a regulatory conflict-control loop, consisting of a conflict-monitoring component (the dorsal anterior cingulate cortex) that detects any type of processing conflicts, and which forwards a conflict signal to a strategic control component (the dorsolateral prefrontal cortex) that in turn aims to resolve conflict by reinforcing top-down biasing processes associated with the current task set [1].

The fact that conflict-driven adjustments in performance have been documented across diverse tasks [2–6], in which conflicts might be generated in different ways, has raised the question whether conflict-driven control mechanisms operate in a conflict-specific manner. In the original model, the conflict-control loop is 'domain-general', in that the output of the conflict monitor does not convey the type or origin of conflict, and results in a quantitative but not qualitative change in top-down biasing [1]. For illustration, consider a task set that entails various top-down biasing processes, in a task in which several conflicts can arise from different sources. Assuming a domain-general

conflict-control mechanism, the occurrence of any type of conflict would trigger an enhancement of all top-down biasing processes involved in the task set and should, therefore, lead to enhanced resolution of other types of conflict that might arise within the same task. However, if conflict-driven control were domain-specific, a given type of conflict would trigger an up-regulation only in the specific top-down biasing process(es) involved in resolving that particular conflict, leaving the resolution of other conflicts unaffected. If conflict-resolution were indeed conflict-specific, this would raise the additional question of whether conflict-resolution was mediated by a single control resource that flexibly resolves different conflicts in a conflict-specific manner, or by several specialized conflict-control loops that can operate in parallel.

Several recent studies have produced data of relevance to these questions [6–14], with some authors concluding that conflict-driven control generalizes across different types of conflict [9,13], others concluding that control acts in a conflict-specific manner [6–8,10,12], and yet others reporting both domain-general and domain-specific effects [8,11]. Here, I argue that the majority of studies cited to support any one of these conclusions suffer from important methodological limitations. By mapping out methodological desiderata for assessing the specificity of conflict-driven control, and by vetting extant studies against these criteria, I conclude that the literature to date indicates that conflict-driven control is domain-specific and probably mediated by multiple independent conflict-control loops.

Establishing independent types of conflict

The main line of empirical support for conflict-driven control stems from the so-called 'conflict adaptation effect' [15] (for a recent review, see Ref. [16]) (Box 1) in stimulus-response compatibility (SRC) tasks (Figure 1). Here, the level of interference from task-irrelevant stimulus information ('conflict'), reflected in slowed responses and decreased accuracy for incompatible relative to compatible stimuli, is found to be reduced after the processing of an incompatible as compared with a compatible stimulus [2,16]. The conflict-monitoring model attributes this phenomenon to a conflict-driven adjustment in cognitive control: because control has been up-regulated in response to conflict on the previous (incompatible) trial, the effect of task-irrelevant stimulus information on the current trial is diminished [1]. Sequential effects of this nature have been observed across a range of SRC paradigms, including variations on the Stroop task [3] (Figure 1a), the Eriksen

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Box 1. The conflict adaptation effect and its caveats

Conflict adaptation refers to a first-order sequence effect in SRC tasks initially reported by Gratton and colleagues [2], described in Figure 1. The conflict-monitoring model explains this effect by supposing that, after an incompatible stimulus (which creates conflict), cognitive control enhances the processing of task-relevant stimulus information. This leads to a speed-up on incompatible trials, reflecting reduced interference by incompatible irrelevant stimulus information, and a slow-down on compatible trials, reflecting reduced facilitation by compatible irrelevant stimulus information [1]. However, this interpretation has been challenged by alternative, associative accounts. Mayr and colleagues [15] pointed out that in SRC tasks that employ only two stimulus values (such as the examples shown in Figure 1 in the main text), half of the transitions between two incompatible stimuli and between two compatible stimuli constitute direct stimulus (and response) repetitions, leading to repetition priming effects, whereas transitions between compatible and incompatible stimuli never involve direct stimulus repetitions. Another associative account is Hommel's 'feature integration model' [41], which assumes that stimulus and response features on each trial are bound together in an episodic memory trace, and automatically retrieved when any of the features re-occur. In SRC tasks with two stimulus values, transitions between two compatible or two incompatible stimuli either involve a complete repetition (facilitating processing) or complete change of stimulus and response features (leaving processing unimpeded), whereas transitions from compatible to incompatible stimuli (and vice versa) are associated with 'partial repetitions', where some features re-occur but others do not. The latter are thought to slow down processing because previous associations between stimulus and response features have to be overcome [41]. Nevertheless, studies that explicitly controlled for repetitions of stimulus and response features (by employing larger stimulus sets) have documented that conflict adaptation persists in the absence of feature integration and repetition priming effects [3,22,25–27,42–44]. Overall, the literature indicates that both associative and conflict adaptation processes contribute to sequential SRC task performance, but that their effects can be disentangled [16].

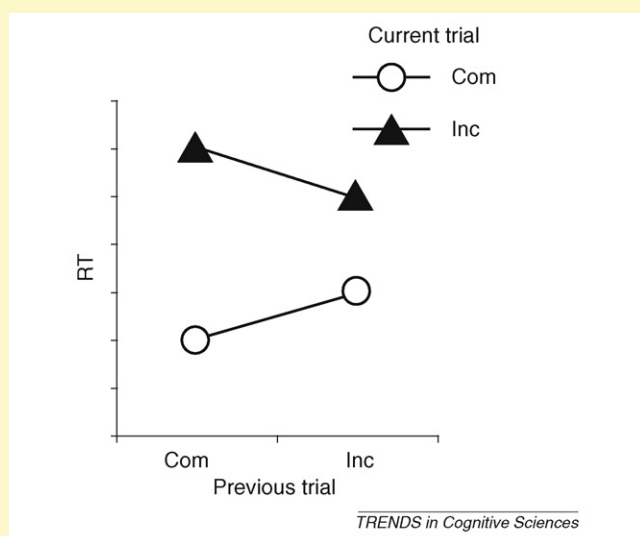


Figure 1. Schematic depiction of conflict adaptation in response time data. Conflict adaptation is characterized by a main effect of current trial compatibility (slower responses to incompatible [Inc] as compared to compatible [Com] stimuli) that is modulated by compatibility on the previous trial, with the current trial compatibility effect being reduced subsequent to incompatible as compared to compatible stimuli. Notably, this interaction between the effects of previous and current trial compatibility is mediated both by a speed-up in the response to incompatible stimuli and a slow-down in the response to compatible stimuli, after an incompatible stimulus.

flanker task [2] (Figure 1b), the Simon task [5] (Figure 1c), the spatial Stroop task [6] (Figure 1d) and the prime-target paradigm [4].

The common experimental strategy for gauging the specificity of conflict-driven control consists of constructing a protocol that combines two different SRC tasks and comparing conflict adaptation effects across trial sequences in which either the same type of conflict is repeated or in which conflicts alternate [6–14]. If control recruited by one type of conflict were to facilitate the resolution of the other type, this would offer evidence for domain-general conflict-resolution, whereas an absence of such cross-conflict adaptation effects would support claims for domain-specific conflict resolution. However, the validity of these interpretations hinges on the premise that the chosen experimental manipulation actually combines two distinct (independent) types of conflict. If the conflicts were to be of the same type, predictions derived from domain-general and domain-specific hypotheses would not differ.

How do we know that two SRC tasks induce independent conflicts? First, a theoretical analysis can enable one to determine whether different tasks are likely to share sources of conflict. An in-depth treatment of this kind is the 'dimensional overlap' taxonomy of SRC effects by Kornblum and colleagues [17], which identifies three potential sources of compatibility (conflict) effects, an overlap between an irrelevant and a relevant stimulus dimension, an overlap between an irrelevant stimulus dimension and a response dimension, and an overlap between the relevant stimulus dimension and a response dimension (Figure 1). Importantly, it transpires from Kornblum's analysis that superficially distinct SRC paradigms can share dimensional overlaps, and thus, sources of conflict. Note that the examples supplied in Figure 1 only describe typical versions of some SRC tasks, and that other variations of these paradigms could be associated with different dimensional overlap profiles. Regardless, the general point being made here is that, on the basis of theoretical reasoning alone, the mixing of SRC tasks that are likely to share sources of conflict [6,9,11] does not lend itself well to testing the domain-specificity of conflict adaptation.

Second, it is necessary to test the independence of processing conflicts empirically because model-based assumptions might be wrong. Furthermore, even if two types of conflict originated with different sources, they could nevertheless lead to overlapping conflicts at subsequent levels of processing, such as the response selection stage, and, therefore, the relative timing of conflict effects at different processing stages might ultimately determine whether their effects on behavior are independent (additive) or interactive [18]. Hence, before assessing potential cross-conflict adaptation effects, it is paramount to establish empirically the independence of the conflicts involved. This can be achieved by creating factorial combinations of SRC tasks and testing for an interaction between the compatibility effects [18–20]; if the compatibility effects do not interact with each other (i.e. they are additive), one can conclude with reasonable certainty that the conflict types are independent. Unfortunately, only few experiments addressing the specificity of conflict adaptation

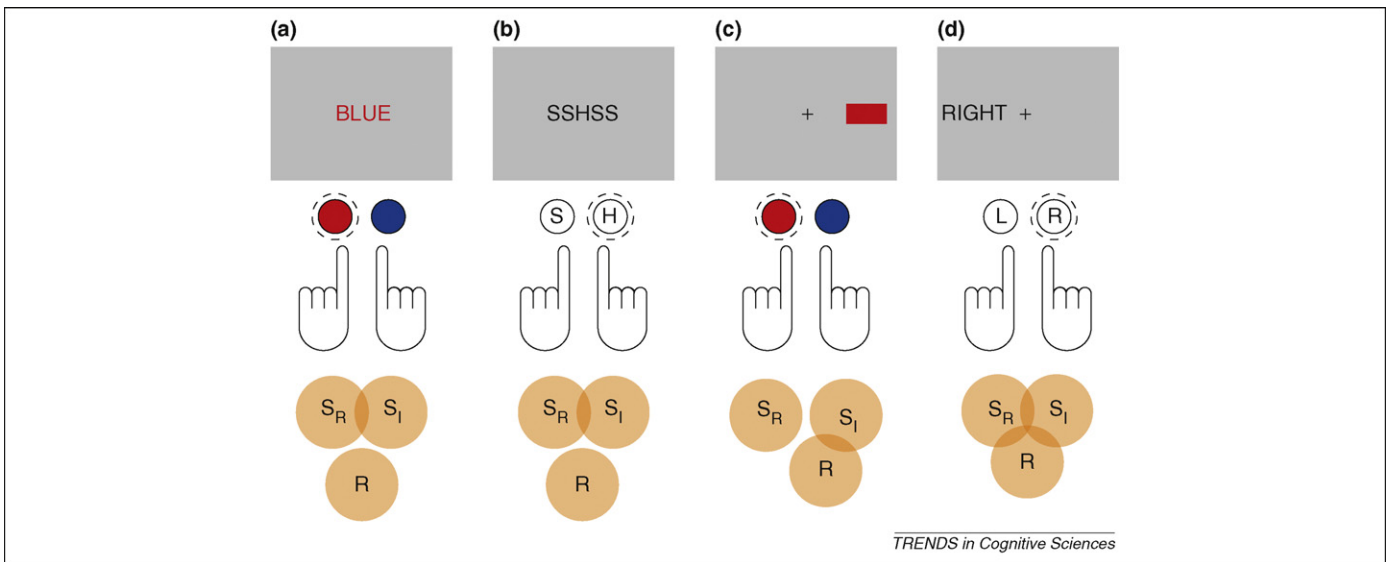


Figure 1. Stimulus-response compatibility tasks and sources of conflict. The top row of each panel shows example stimuli of common stimulus-response compatibility (SRC) tasks. The middle row displays response options, with the broken circle option indicating the correct response to the above stimulus. The bottom panels display potential sources of compatibility (conflict) effects for each task, by showing ‘dimensional overlaps’ [17] between task-relevant stimulus dimensions (S_R), task-irrelevant stimulus dimensions (S_I) and the response dimension (R). It is important to note that, although some of these tasks differ in their sources of compatibility effects, incompatible stimuli in each task ultimately lead to response competition. **(a)** The color-naming Stroop task [37]: subjects are required to respond to the ink color (S_R) of a color-word, while ignoring the meaning of the word (S_I). Ink color and word-meaning have a semantic overlap and can, therefore, be compatible (e.g. the word RED printed in red) or incompatible (e.g. the word BLUE printed in red) with each other. **(b)** The Eriksen flanker task [38]: subjects are required to respond to a central letter (letters) and can, thus, be compatible (e.g. HHHHH) or incompatible with each other (e.g. SSHSS). **(c)** The Simon task [39,40]: subjects are required to respond to the color of a stimulus (S_R) that can be displayed to the left or right of fixation, while ignoring the stimulus location (S_I). The stimulus location (left or right) has a dimensional overlap with the response dimension (R) (left or right hand button push) and can, therefore, be compatible (e.g. a red stimulus presented on the left hand side) or incompatible (e.g. a red stimulus presented on the right hand side) with the response. **(d)** The spatial Stroop task [39]: subjects are required to respond to the word-meaning (S_R) of directional word stimuli (LEFT, RIGHT) while ignoring their location (S_I) to the left or right of fixation. (This assignment of relevant and irrelevant stimulus dimensions can also be reversed.) Here, a dimensional overlap between stimulus location and word-meaning can give rise to compatible (e.g. RIGHT displayed on the right hand side) or incompatible (e.g. RIGHT displayed on the left hand side) stimuli. Furthermore, both the irrelevant and the relevant stimulus dimensions have overlaps with the response dimension (R) (a left or right hand button push), which can give rise to additional compatibility effects.

have probed the inter-dependence of conflicts in their design in this manner [7,10,11,14].

Assessing the specificity of conflict-driven control

Once the independence of two types of conflict has been established, the question arises how to best combine them

to assess whether control processes triggered by one type of conflict generalize to the resolution of another. Three approaches can be found in the literature: ‘task-switching’ designs [8–10,13], ‘stimulus-switching’ designs [6,12,14] and ‘factorial task-crossing’ designs [7,11,14] (Figure 2). In task-switching designs, the relevant and irrelevant

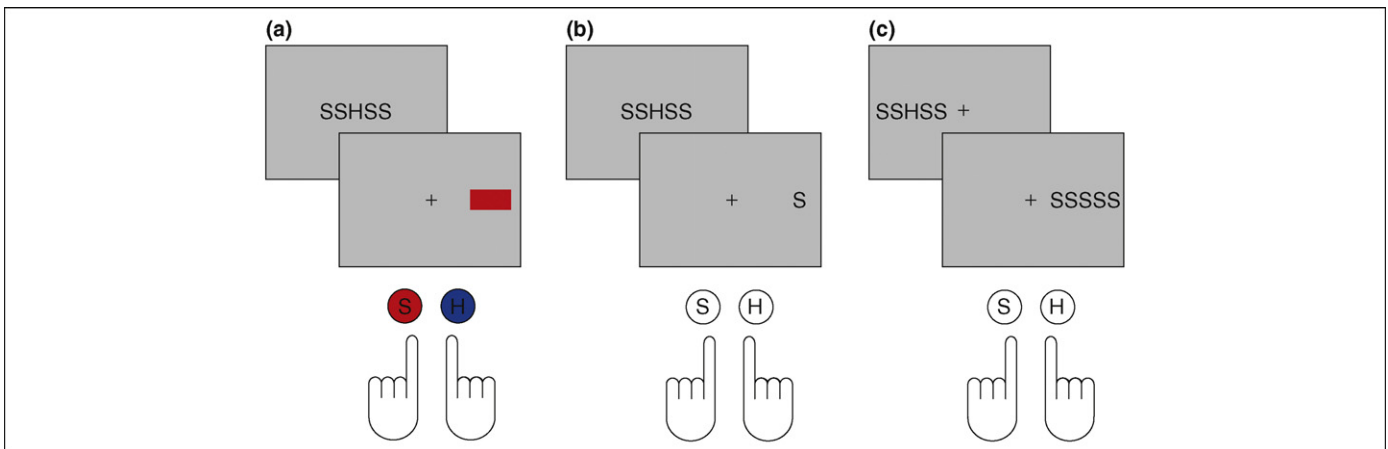


Figure 2. Experimental strategies for assessing the specificity of conflict-driven control mechanisms. Depicted are examples of how one could combine the flanker and Simon tasks to gauge whether flanker task conflict affects the resolution of Simon task conflict, and vice versa. **(a)** The ‘task-switching’ design: flanker task trials are randomly interspersed with Simon task trials, such that relevant and irrelevant stimulus features, in addition to stimulus-response mappings can switch between trials. In the example pictured, an incompatible flanker stimulus is followed by an incompatible Simon stimulus. **(b)** The ‘stimulus-switching’ design: the task-relevant stimulus feature and stimulus-response contingencies are preserved across trials, but the task-irrelevant stimulus features (flankers versus stimulus location) can switch between trials. In the example shown, an incompatible flanker stimulus is followed by an incompatible Simon stimulus. **(c)** The ‘task-crossing’ design: the task-relevant stimulus feature and stimulus-response contingencies are constant across trials, whereas the task-irrelevant stimulus features (flankers and stimulus location) are combined in a factorial manner. In the example shown, the first stimulus is incompatible with respect to both the flanker and the Simon stimulus dimensions, whereas the second stimulus is compatible with respect to the flanker dimension but incompatible with respect to the Simon dimension.

stimulus characteristics, in addition to the stimulus-response contingencies, might switch between trials. In stimulus-switching designs, relevant stimulus characteristics (and response contingencies) are identical between trials but the task-irrelevant stimulus characteristics might switch. In factorial task-crossing designs, relevant stimulus characteristics (and response contingencies) are identical between trials, whereas task-irrelevant characteristics are combined in a factorial fashion.

To illustrate, consider how the flanker and Simon tasks, depicted in Figure 1, could be combined. The task-switching approach would consist of interspersing ‘pure’ flanker and Simon task trials (Figure 2a) and to measure whether compatibility effects in one task are reduced after incompatible trials of the other task. However, this strategy is problematic because switches between conflict types are perfectly confounded with task switches: at each transition between flanker and Simon conflicts, the subject has to retrieve task-specific stimulus-response associations and reconfigure processing priorities accordingly. Because task-switching in itself is reliant on cognitive control resources [21], as reflected in behavioral ‘switch costs’, task-switching effects are likely to mask and/or interact with conflict-driven adjustments in control [22]. Empirical studies have shown that task-switches preceded by incompatible trials are associated with a greater cost than those preceded by congruent trials [23,24]. It is tempting to interpret this interaction between compatibility and task-switching effects as supporting the hypothesis of conflict-specific adaptation effects, based on the assumption that an incompatible stimulus in one task triggers a conflict adaptation process that ‘misdirects’ resources

required for dealing with a different type of conflict in the other task. However, this effect could alternatively reflect a generic delay in task set reconfiguration subsequent to dealing with a cognitively demanding (incompatible) trial, irrespective of the nature of conflict resolution strategies used on either task. In sum, these considerations indicate that task-switching designs [8–10,12,13] are not well-suited to determine the specificity of conflict-driven control mechanisms.

After the stimulus-switching approach, one could intersperse standard flanker task trials with trials in which single target letters are presented in peripheral positions, akin to Simon task stimuli [14] (Figure 2b). Here, the subjects apply an identical mapping between task-relevant stimulus information and responses across trials, which could, in theory, prevent task-switching effects. The stimulus-switch approach nevertheless harbors some drawbacks. First, the different types of conflict constitute two levels of a single factor in this design, such that they cannot be varied independently of each other (each trial is either a flanker trial or a Simon trial). This precludes the possibility of assessing interaction effects between the two types of conflict [6], which would be necessary for empirically determining that their main effects are independent of each other (this criticism also applies to task-switching designs). Second, although subjects are technically performing a single task, the fact that the different conflict conditions involve perceptually very distinct stimulus configurations (Figure 2b) might nevertheless introduce a *de facto* task switch. This intuition is supported by the observation of switch costs in this type of design, reflected in a general increase in response time for switches between

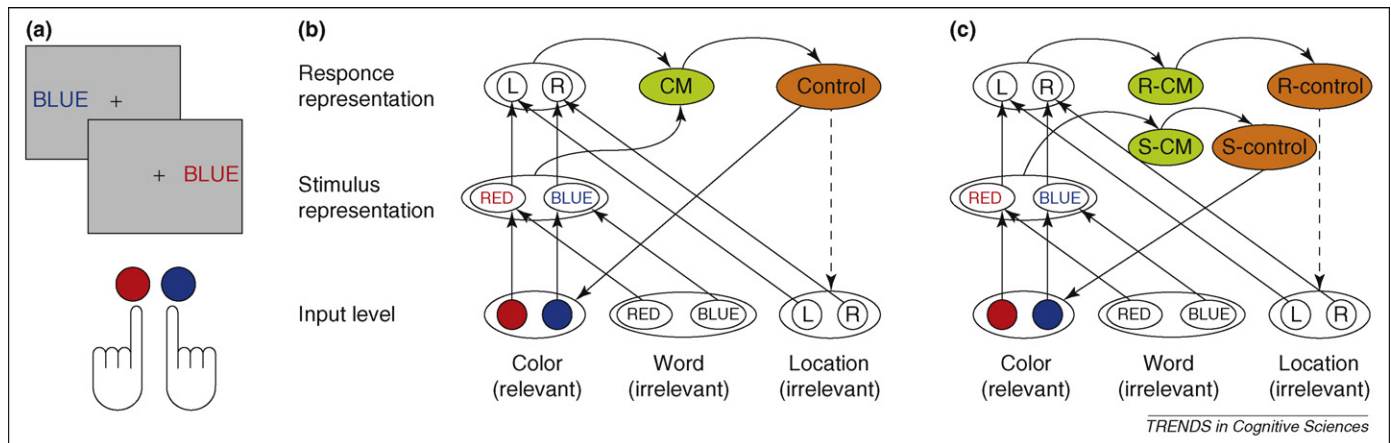


Figure 3. Domain-general and domain-specific models of conflict-adaptation in the context of a combined Stroop-Simon task. (a) A factorial task-crossing design combines Stroop and Simon tasks by presenting color-word stimuli at peripheral locations [7,14,18–20]. In the example shown, the first stimulus is compatible with respect to the Stroop stimulus dimension and incompatible with respect to the Simon stimulus dimension, whereas the second stimulus is incompatible with respect to both dimensions. Stroop and Simon compatibility effects in this protocol do not interact [7,14,18–20], and conflict adaptation effects are conflict-specific: each type of conflict facilitates the resolution of its own kind, but does not affect the resolution of the other kind [7,14]. (b,c) In both the domain-general (b) and the domain-specific (c) model, task-relevant (color) and task-irrelevant stimulus information (word-meaning and stimulus location) serve as inputs to stimulus and response processing stages. The stimulus processing stage represents the semantic concepts of ‘red’ and ‘blue’, regardless of whether they originate with verbal or color information, and is susceptible to conflict stemming from a dimensional overlap between irrelevant and relevant stimulus information (i.e. Stroop conflict) [17]. The response selection stage (L, left; R, right) receives input from the stimulus processing stage but is also affected by stimulus location and is, therefore, liable to conflict from a dimensional overlap between the location of the response effectors and the stimulus location (i.e. Simon conflict) [17]. (b) In the domain-general model, a single ‘all-purpose’ conflict monitor (CM) receives conflict signals from both stimulus and response processing stages and the summed level of conflict reinforces a generic task-set ‘control’ module, which enhances the processing of relevant stimulus information [25] and inhibits (broken line) the impact of irrelevant location information [5]. Because neither the conflict monitor nor the control module differentiate between different sources of conflict, the occurrence of Stroop (or Simon) conflict would facilitate the resolution of both Stroop and Simon conflicts, thus producing cross-task conflict adaptation effects, contrary to empirical data [7,14]. (c) In the domain-specific model, conflict signals from the stimulus and response processing stages feed into conflict-specific monitoring units (R-CM, response-conflict monitor; S-CM, stimulus-conflict monitor), which in turn recruit conflict-specific control strategies, such that stimulus (Stroop) conflict would lead to enhanced amplification of task-relevant stimulus information [25], and response (Simon) conflict would lead to enhanced inhibition of task-irrelevant location information [5]. In this way, the domain-specific model architecture predicts the conflict-specific adaptation effects observed in empirical data [7,14].

irrelevant stimulus dimensions, irrespective of compatibility effects [12].

Finally, the factorial task-crossing approach could combine flanker and Simon tasks by presenting the flanker stimuli at peripheral locations [14,18] (Figure 2c), such that each stimulus can be compatible or incompatible with respect to both flanker and Simon conflicts at the same time. This design avoids any task switching effects and facilitates the assessment of independence between Simon and flanker conflicts through the analysis of compatibility interaction effects. For assessing the specificity of conflict adaptation, this analysis would simply need to be expanded to encompass previous trial compatibility factors [7,11,14]. Importantly, the fact that the different types of conflict are manipulated simultaneously in this design also enables one to distinguish between two alternative possibilities of how conflict-specific control effects might arise: there could be a single control resource that resolves different conflicts with conflict-specific strategies, or there could be separate (independent) conflict-specific control resources. The latter could only be established with a factorial task-crossing design, by showing that the simultaneous detection and resolution of different conflicts does not result in either mutual facilitation or impairment of conflict adaptation effects.

Conflict-specific cognitive control mechanisms

Only a few studies in this literature have employed factorial task-crossing designs. Two experiments factorially combined the Stroop and Simon tasks (Figure 3a), and both found these conflict types to be non-interactive, and that each conflict enhances the resolutions of its own kind, but does neither facilitate nor impair the resolution of the other [7,14]. In another experiment, a factorial combination of the flanker and Simon tasks resulted in conflict-specific, but not conflict-general, adaptation effects [14]. However, any interpretation of this result is hampered by the facts that no main effect of Simon compatibility was observed, and that Simon and flanker compatibility effects interacted sub-additively [14], indicating overlapping conflicts. Finally, another study factorially combined a spatial prime-target paradigm with a Simon task [11], and, in addition to strong within-conflict adaptation effects, reported evidence for weaker cross-conflict adaptation effects. However, the spatial prime-target and Simon task compatibility effects also displayed a sub-additive interaction [11], indicating that the conflicts produced by these protocols were not independent, and this overlap between conflicts could account for the 'cross-conflict' adaptation effects observed.

Overall, results from these studies are concordant with the hypothesis of conflict-specific strategies of conflict resolution. Intriguingly, they also provide support for a somewhat more radical proposal, namely that conflict-specific control is mediated not by a single resource of conflict-driven control but, rather, by multiple, independent conflict-specific control mechanisms (Figure 3b,c). Specifically, the data indicate that the brain is capable of simultaneously and independently detecting and resolving conflict stemming from incompatibility between relevant and irrelevant stimulus dimensions, and conflict

Box 2. Local versus global conflict detection

Recent data indicate the existence of various specialized and anatomically segregated conflict-resolution mechanisms for dealing with different types of conflict [7,26,27]. This evokes the question whether different conflicts are nevertheless detected by a domain-general conflict-monitor, as proposed by the conflict-monitoring model [1]. Neuroimaging data on this issue have been equivocal [26,45–47]. From a theoretical standpoint, a global monitoring device would require some unspecified means for determining the origin of conflict, so that appropriate, conflict-specific resolution mechanisms could be triggered (see also Ref. [36]). Conversely, 'local' conflict detectors would by definition deal with a specific type of conflict, thus circumventing this problem [48]. More fundamentally, it can be argued that regulatory conflict-control mechanisms do not necessitate a dedicated conflict-monitoring device; the mere presence of conflicting sensory or motor representations could suffice for triggering adaptation processes. From this perspective, the commonly observed activation in anterior cingulate cortex during the processing of incompatible stimuli would be a reflection of the occurrence of conflicting response-related representations in pre-motor cortex rather than of the detection of such conflict [49].

How could local conflict detection be implemented? One perspective on this question is to view conflict adaptation not in terms of a limited set of discrete, specialized monitoring and control resources, but rather as a functional organizing principle of cognition that can occur across all levels of the neural processing hierarchy (from sensory, to association, to motor cortices). For instance, like the response nodes in the conflict-monitoring model [1], nodes at each level of a hierarchical neural network integrate input from multiple nodes at the subordinate level, with the origin of the strongest input determining the nature of the output of the node to the next higher level. Whenever signals from different input nodes are of similar magnitude, uncertainty (conflict) arises as to which signal to relay. Such 'local' conflict at any level of the processing hierarchy could be propagated upwards to trigger top-down feedback to help disambiguate the inputs, similar to the way in which feed-forward 'prediction error' in hierarchical Bayesian models of perception triggers a cascade of adjustments in top-down predictive feedback at higher processing levels [50].

stemming from incompatibility between an irrelevant stimulus dimension and a response dimension [7,14]. Unless one assumes unlimited processing resources on behalf of a single conflict-triggered 'controller', these data indicate the existence of independent conflict-control mechanisms that can operate in parallel [7] (Figure 3; see also Box 2). Note, however, that results from these studies are also open to interpretations invoking associative rather than conflict-driven mechanisms [14] (Box 1). Clearly, additional studies employing larger stimulus sets are required for corroborating the current conclusions. Data from neuroimaging studies, however, support the notion of conflict-specific control mechanisms, indicating that the neural strategies involved in the resolution of Stroop and Simon conflicts consist of the excitatory biasing of stimulus representation in sensory cortex [25] and of inhibitory biasing of response preparation processes in motor cortex [5], respectively [7]. Other recent studies have supplied evidence for dissociable neural circuits of conflict resolution, the recruitment of which varies with the affective content of task-irrelevant stimulus information, indicating that there is a specialized mechanism for resolving interference stemming from the prioritization of emotionally salient stimuli by the limbic system [26,27].

But is it 'control'?

The fact that two conflict resolution processes can occur in parallel, without affecting each other, could provoke the argument that conflict adaptation does not actually represent an instance of controlled processing because such processing has traditionally been defined precisely through its liability to interference by simultaneous demands on cognitive control [28]. This, however, represents a circular argument because this traditional yardstick for controlled processing presupposes a single, limited resource of control in the first place. Furthermore, the fact that different conflict resolution processes do not interfere with each other does not imply that these processes are immune to other resource constraints [29]. Nevertheless, it is worth noting that the sense in which conflict adaptation constitutes controlled processing might be more closely aligned with the concept of control as derived from the study of self-regulating systems, in which a thermostat would be considered an agent of control, than with the traditional usage of this term in psychology, in which controlled processes have been defined as those that require conscious effort and attention, as opposed to 'automatic' processes that do not [28]. In principle, conflict adaptation does not necessitate the presence of awareness or intentions on behalf of the subject [1,30] (but see Ref. [4]). Furthermore, given the 'reactive' nature of conflict adaptation, it seems quite plausible that, once a task set has been established, on-task conflict adaptation processes could be triggered and implemented 'automatically'. This scenario, if true, should not render conflict adaptation any less interesting to scholars of cognitive control, however, but rather more interesting because it is the understanding of flexible goal-directed behavior in terms of a collection of 'simpler' mechanisms that ultimately holds the promise of eschewing an omni-cognizant homunculus from our models of high-level cognition [31].

Conclusions

I have argued that many of the recent studies seeking to address whether conflict-triggered control mechanisms operate in a conflict-specific fashion, suffer from potential confounds related to non-independence of conflict types and task-switching effects, and that these issues can be overcome by an experimental strategy that combines different SRC tasks in a fully factorial design. The limited literature pursuing this strategy indicates that conflict adaptation processes are domain-specific and, intriguingly, that these effects might be mediated by the workings of multiple, conflict-specific control mechanisms that operate independently. After this argument, an obvious goal for future research in this area is to carefully delineate distinct conflict-control loops in detail. Several other outstanding questions concern the relationship between conflict adaptation and other forms of control, in addition to associative processes (Box 3). Conflict adaptation represents a 'reactive' adjustment of processing priorities in response to an internal signal of performance difficulty, whereas many other instances of cognitive control are 'prospective' in nature, such as the use of an explicit cue to guide the anticipatory allocation of processing resources. It is currently not clear how these control processes relate to each

Box 3. Questions for further research

- How does conflict adaptation interact with associative processes that might link context, stimulus and response features?
- How do 'reactive', conflict-triggered control mechanisms relate to more 'prospective' control processes, such as advance preparation based on external cues?
- How would conflict-specific adaptation mechanisms be accommodated in other models of cognitive control?
- Are there clinical populations that display selective impairment in resolving a particular type of conflict?

other and whether they rely on distinct neural resources. Regarding associative processes, recent work indicates that control over conflict can be guided by associative learning: in cases in which task-irrelevant stimulus information predicts the likely presence of conflict, processing adjustments have been reported to be item-specific [32]. Although some of the data supporting this notion can be accounted for by pure stimulus-response learning [33], other studies indicate that context-specific adaptation is genuine [34], and computational models are being developed to account for this phenomenon [35,36]. However, much remains to be learned in this area.

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