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Review article

Conflict detection and resolution rely on a combination of common and distinct cognitive control networks

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A B S T R A C T

Cognitive control can be activated by stimulus–stimulus (S-S) and stimulus-response (S-R) conflicts. However, whether cognitive control is domain-general or domain-specific remains unclear. To deepen the understanding of the functional organization of cognitive control networks, we conducted activation likelihood estimation (ALE) from 111 neuroimaging studies to examine brain activation in conflict-related tasks. We observed that fronto-parietal and cingulo-opercular networks were commonly engaged by S-S and S-R conflicts, showing a domain-general pattern. In addition, S-S conflicts specifically activated distinct brain regions to a greater degree. These regions were implicated in the processing of the semantic-relevant attribute, including the inferior frontal cortex (IFC), superior parietal cortex (SPC), superior occipital cortex (SOC), and right anterior cingulate cortex (ACC). By contrast, S-R conflicts specifically activated the left thalamus, middle frontal cortex (MFC), and right SPC, which were associated with detecting response conflict and orienting spatial attention. These findings suggest that conflict detection and resolution involve a combination of domain-general and domain-specific cognitive control mechanisms.

1. Introduction

Cognitive control is the ability to orchestrate thought and action in accordance with internal goals (Miller and Cohen, 2001). It has been conceptualized as a set of control functions that may include working memory, response selection, response inhibition, and task switching (Lenartowicz et al., 2010; Sabb et al., 2008). Its core system, the fronto-parietal network (FPN), meaningfully contributes to a variety of task contexts. The FPN allows rapid reconfiguration of information flow across multiple task-relevant brain networks, such as the visual network, auditory network, and default mode network (Cole et al., 2013). Alterations of this control system might contribute to a striking range of mental diseases (Cole et al., 2014). In the laboratory, various stimulus-response compatibility (SRC) tasks, such as the Stroop task (Stroop, 1935), the Eriksen flanker task (Gratton et al., 1992), and the Simon task (Simon and Small, 1969), have been employed to study cognitive control functionality. The SRC effect is the phenomenon in which performance is worse (i.e., slower and more erroneous) when mappings of stimuli to responses are incongruent than when they are congruent (Fitts and Seeger, 1953; Proctor and Vu, 2006).

Based on the distinct SRC tasks, several researchers have put forward brain network models of cognitive control from an attention perspective. Fan et al. (2005) proposed three separable anatomical networks related to the components of attention. The alerting network, the orienting network, and the executive control network activate the thalamic, parietal, and anterior cingulate cortex, respectively. Corbetta and Shulman (2002) identified two partially segregated attentional systems. The top-down system, which includes parts of the intraparietal cortex and superior frontal cortex, is involved in preparing and applying goal-directed selection. The bottom-up system, which includes the temporoparietal cortex and inferior frontal cortex, is specialized for the detection of behaviorally relevant, salient or unexpected stimuli.

Different from two attention networks involved in cognitive control, Botvinick et al. (2001) proposed the conflict-monitoring (CM) model of cognitive control. This model describes a single, "all-purpose" conflict-control loop that can be recruited to generally handle different types of conflicting representations; the loop comprises the anterior cingulate cortex (ACC) for conflict detection and the prefrontal cortex for executive control (Botvinick et al., 2001). According to the CM model, many types of conflicts will yield highly similar patterns of brain activation because they share a centralized module of cognitive control. The expanded parallel distributed processing (PDP) model further

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suggests that the mechanisms of cognitive control are adaptive and self-regulating (Botvinick and Cohen, 2014). The model proposes that the anterior cingulate cortex implements the conflict monitoring by modulating the activity of control representations, and dopamine assists the adaptive gating by regulating the updating of control representations in the prefrontal cortex. However, according to the dimensional overlap (DO) model proposed by Kornblum et al., SRC effects can occur independently when at least two of three dimensions (task-relevant stimulus dimension, task-irrelevant stimulus dimension, and response dimension) overlap (Kornblum, 1994). In a typical Stroop task, the SRC effect involves stimulus-based processing (S-S conflict) as the conflict stems from incongruence between task-relevant (S_R, e.g., ink color) and task-irrelevant (S_I, e.g., word meaning) stimulus features (Egner et al., 2007; Liu et al., 2010). In a typical Simon task, the SRC effect involves response-based processing (S-R conflict) as the conflict results from incongruence between a task-irrelevant stimulus feature (S_I, e.g., the location of the stimuli) and a response feature (R, e.g., button press) (Egner et al., 2007). Under this definition, S-S and S-R conflicts belong to distinct DO types and are resolved by distinct control mechanisms. Supporting the DO model, the domain-specific model further proposes that specific conflict-control loops are involved in processing S-S and S-R conflicts (Egner, 2008). The model suggests that the SRC effects that stem from S-S and S-R conflicts uniquely activate specific brain regions because distinct cognitive control mechanisms are engaged in parallel by S-S and S-R conflicts.

Functional magnetic resonance imaging (fMRI) studies might provide insight into these theoretical debates and issues because they have the potential to demonstrate whether S-S and S-R conflict processing engage common or distinct brain mechanisms. Previous fMRI studies manipulating S-S and S-R conflicts have found that the brain uses distinct but parallel cognitive control mechanisms to resolve these different forms of cognitive interference (Egner et al., 2007; Liston et al., 2006; van Veen and Carter, 2005). In contrast, some studies have found that although the specific brain activation patterns are not identical across conflict domains, S-S and S-R conflicts share a common neural mechanism of attentional control and top-down modulation (Fan et al., 2003; Jiang and Egner, 2014; Kim et al., 2010; Kim et al., 2011; Liu et al., 2004; Milham et al., 2001). Some studies have even found completely overlapping activations across conflict domains (Peterson et al., 2002).

The differing results in conjunction with confounding factors make it difficult to obtain a clear understanding of the conflict-control processes in the human brain. First, the heterogeneity of the results is partly due to diverse experimental paradigms developed by various research groups that have aimed to address different aspects of cognitive control, such as motivation (Soutschek et al., 2014), attentional switching (Kim et al., 2012), and anticipatory control processes (Aarts et al., 2008). Second, it is unknown whether activation patterns reflect information processing relevant to the cognitive control process itself or serve incidental functions. Although an fMRI study harnessed multivoxel pattern analysis (MVPA) decoding S-S and S-R conflicts to overcome these limitations of traditional studies and showed a hybrid architecture of conflict processing entailing both domain-specific and domain-general components (Jiang and Egner, 2014), a single study is unlikely to provide decisive results regarding cognitive control processing.

Therefore, it is crucial to pool prior studies together and examine the core common and distinct conflict-processing networks in the human brain by combining theory-driven and data-driven approaches. One method of meta-analysis, activation likelihood estimation (ALE) (Turkeltaub et al., 2002), allows statistically verifiable concurrence across functional neuroimaging studies, revealing regions with the highest “likelihood” of activation, i.e., regions in which concurrence is highest.

The main goal of the current study is to assess whether cognitive control mechanisms underlying DO conflicts are general or distinct by performing a meta-analysis of the results of 111 recent neuroimaging studies. Three different patterns of results that relate to different cognitive control models are possible. 1) Domain-general activation. According to the CM model and expanded PDP model, which initially insisted on an all-purpose control module, cognitive control areas associated with S-S and S-R conflict processing would be activated completely consistently. 2) Domain-specific activation. Based on the DO model and the domain-specific model, S-S and S-R conflicts would show separate neural activation patterns because of their conflict-specific processing strategies. 3) Mixed activation. However, considering the inefficiency of conflict processing by a unitary control process and the impossibility of endless control mechanisms for each potential source of conflict, the combination of domain-general and domain-specific models is a more reasonable explanation. Specifically, we expected a hybrid neural architecture of conflict-control involving both specific and general brain areas to process S-S and S-R conflicts.

2. Methods

2.1. Literature search and organization

2.1.1. Study identification

Four independent researchers conducted a thorough search of the literature for fMRI studies examining S-S and S-R conflict processing in humans. The terms used to search the online citation indexing service PUBMED (through July 2017) were “fMRI” and “Stroop/Flanker/SNARC/Simon/Navon/Global-Local” by the first researcher, and “functional magnetic/resonance imaging/fMRI” in the abstract and “Stroop/Flanker/SNARC/Simon” in all fields by the second researcher. The terms used to search the online citation indexing services PUBMED (through July 2017), EBSCO, and Web of Science were “fMRI/brain” and “Stroop/Flanker/SNARC/Simon/conflict/Navon/Global-Local” by the third researcher. The terms used to search the online citation indexing service PUBMED (through July 2017) and Google Scholar were “fMRI/MRI/PET”, “Stroop/Flanker/SNARC/Simon/Navon/stimulus-response compatibility” and “response eligible” by the fourth researcher. All resulting articles were pooled into a database, and redundant entries were eliminated. The initial search results were merged to produce a total of 1832 articles. Several exclusion criteria were then applied to eliminate articles that were not directly relevant to the current study. The exclusion criteria were as follows: 1) the study was not a primary empirical study (e.g., review articles); 2) the study did not report results in standard stereotactic coordinate space (either Talairach or Montreal Neurological Institute, MNI); 3) the study used tasks unrelated to the DO framework, for example, the stop-signal task (Hendrick et al., 2010), which has been widely used to study inhibition control, but involves no overlap among stimulus or response dimensions; 4) the study was related to S-S or S-R conflict processing that was not “pure” due to the overlapping of the relevant stimulus dimension, irrelevant stimulus dimension, or response dimension with each other; for example, the Flanker task mixed with visual search (Wei et al., 2013) was not “pure” conflict, nor was the study influenced by cuing (e.g., Forstmann et al., 2008a) or affective factors (e.g., Comte et al., 2016); 5) the study was of structural brain analyses (e.g., voxel-based morphometry or diffusion tensor imaging); 6) the study was solely based on region of interest (ROI) analysis (e.g., using anatomical masks or coordinates from other studies); 7) the study was of a distinctive population of individuals whose brain function may deviate from those of normal, healthy adults (e.g., children, aging adults, or substance-dependent individuals); and 8) the study did not report the coordinates for the healthy adult group alone. Variability was accepted among methods in which subjects were instructed to report decisions during the tasks (i.e., verbal, nonverbal button press). This search process resulted in 111 articles in the final database (listed in Supplementary Table 1). See Fig. 1 for details regarding the literature search process.

During data extraction, studies were grouped by the following