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**Research Report**

# An ERP investigation of the Stroop task: The role of the cingulate in attentional allocation and conflict resolution

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**ABSTRACT**

The majority of studies support a role of the anterior cingulate cortex (ACC) in the attentional control necessary for conflict resolution in the Stroop task; however, the time course of activation and the neural substrates underlying the Stroop task remain contentious. We used high-density EEG to record visual-evoked potentials from 16 healthy subjects while performing a manual version of the traditional Stroop colour-word task. Difference waveforms for congruent-control and incongruent-control conditions were similar in amplitude and had a similar spatial distribution in the time window of 260–430 ms post stimulus onset. Source estimation indicated particularly middle cingulate involvement in congruent-control and incongruent-control difference waveforms. In contrast, the difference waveform for the incongruent-congruent contrast was observed later (in the time window of 370–480 ms), had a different spatial distribution, and source estimation indicated that the anterior cingulate underlies this difference waveform. As congruent-control and incongruent-control differences have a similar timeframe and cingulate source, we propose that this indicates early attentional allocation processes. That is, the identification of two sources of information (the word and the colour it is printed in) and the selective attention to one. The later peak in the incongruent-congruent difference wave, originating in anterior cingulate, likely reflects identification (and subsequent resolution) of conflict in the two sources of information.

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**1. Introduction**

The Stroop-colour naming task was introduced over 70 years ago (Stroop, 1935) and has, particularly since its ‘rediscovery’ and modification by Klein (Klein, 1964), become the “paradigmatic measure of selective attention” (Carter et al., 1995). The classic Stroop task requires participants to name the colour ink that a colour-word (e.g. RED) is presented in. A robust finding, referred to as the Stroop interference effect, is an increase in the number of errors and the time taken to respond

in incongruent conditions (e.g. when the word BLUE is printed in red ink), relative to either control conditions (e.g. when the word JUMP or XXXX is printed in red ink), or congruent conditions (e.g. when the word RED is printed in red ink). In fact, the latter condition may give rise to what is termed Stroop ‘facilitation’. That is, a decrease in errors and reaction times in this condition relative to control conditions. It is generally thought that these behavioural differences are due to either a conflict between stimuli and responses that result in competition for the allocation of attentional resources

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(Phaf et al., 1990), or a conflict at the level of response selection and monitoring (Dyer, 1973).

The neural correlates underlying Stroop performance are of more than academic interest due to the utility of the Stroop task as a research tool in disorders such as schizophrenia (Barch et al., 1999; Carter et al., 1997; MacLeod and MacDonald, 2000), mania (McGrath et al., 1997), obsessive-compulsive disorder (McGrath et al., 1997), Alzheimer's disease (Fisher et al., 1990), memory dysfunction (Hanninen et al., 1997), and the effects of aging on cognitive control (West and Moore, 2005).

In a review, MacLeod and MacDonald (2000) point to a significant number of positron-emission tomography (PET) (Bench et al., 1993; Carter et al., 1995; George et al., 1994; Pardo et al., 1990) and functional magnetic resonance imaging (fMRI) (Bush et al., 1998; Carter et al., 2000) studies that have compared cerebral activity in the Stroop incongruent condition to activity in a variety of control conditions. In most cases differential activation between incongruent and control conditions is observed in regions of the ACC (see also the meta-analysis of Bush et al. (2000)). However, the comparison of Stroop incongruent and control conditions also reveals activation in a number of other brain regions. One region that is consistently activated is the prefrontal cortex, in particular the DLPFC (MacDonald et al., 2000; Milham et al., 2003). According to Ullsperger and von Cramon (2004), this area of the prefrontal cortex is most likely involved in task preparation. Given the consistent observation of ACC activation in incongruent trials, however, the ACC most likely mediates conflict resolution in the Stroop task (MacLeod and MacDonald, 2000) although it is still a matter of debate as to whether the ACC mediates conflict resolution by applying attentional control or detecting conflicting information or monitoring performance.

Perhaps the most influential view of the role of ACC in tasks such as the Stroop is outlined by Posner and Dehaene (1994). They argue that the ACC is involved in the top-down implementation of selection and processing of stimuli that need to be acted upon and thus has an 'executive' role in the control of attention. Others suggest that in fact the ACC is principally an error detector that monitors performance (Carter et al., 1998; MacDonald et al., 2000) or detects the presence of conflicting information (van Veen and Carter, 2002a). These studies support the conflict monitoring theory of ACC function (Botvinick et al., 1999; Carter et al., 1998). According to this view, the ACC will be activated in conditions where there is conflicting information, as it is recruited to firstly detect such events and secondly signal the need for attentional control. Milham and Banich (2005) suggest that top-down attentional control itself may in fact be mediated by other structures such as the DLPFC (MacDonald et al., 2000). In contrast, Zysset et al. (2001) posit that the ACC is not specifically involved in these processes at all, but rather is involved in response stages, i.e., motor output preparation.

The suggestion that ACC is principally involved in response-related processes is, as has been pointed out by MacLeod and MacDonald (2000), difficult to reconcile with the observation that increased activation in Stroop congruent conditions has been observed relative to control conditions (Bench et al., 1993; Carter et al., 1995). They argue that in the

congruent condition any source of conflict is due to the need to decide which dimension of a word to attend to (colour ink or word). Therefore, since the two sources of information are congruent, response conflict is unlikely. More recently, in an fMRI study, Milham and Banich (2005) provide further evidence of increased ACC neural activity during both congruent and incongruent conditions. However, they suggest a possible functional differentiation within the ACC, with the anterior division of the ACC rostral region being more conflict specific, and the posterior division exhibiting a more generalized pattern with increased activation when task-irrelevant information is present, regardless of conflict.

In summary, the majority of neuroimaging studies implicate the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) in at least some aspects of Stroop-task processing. However, in spite of (or perhaps because of) the large number of Stroop imaging studies, the neural correlates underlying differential Stroop task performance remain contentious. Neuropsychological work has not clarified the issue either. For example, Vendrell et al. (1995) looked at patients with frontal damage and suggested that right prefrontal cortex is the most important region in sustained attention. Stuss et al. (2001) found that damage to bilateral superior medial frontal region resulted in impaired performance in terms of poorer accuracy and slowing down for the incongruent condition, while Naccache et al. (2005) found that a patient with left mesio-frontal cortex lesion including the ACC was slowed down across all conditions compared to healthy subjects on the Stroop task; however, the magnitude of the Stroop effect was comparable to normal subjects.

In contrast to fMRI and PET studies, event-related potential (ERP) studies offer real time temporal resolution of neural processes, allowing a precise analysis of the time course of neural events elicited during a task. One such study identified a P300 that was elicited in various Stroop task conditions. However, while the participants' behavioural reaction-times (RTs) varied with the congruence of the word and the colour in which it was printed, the latency of the concomitantly evoked P300 did not (Duncan-Johnson and Kopell, 1981). The behavioural Stroop effect may therefore be due to competition at the level of the response (Rosenfeld and Skogsberg, 2006), thus supporting "late selection" theoretical accounts.

Late selection accounts argue that the conflict occurs late in processing, most likely at the response stage (MacLeod, 1991). However, subsequent ERP studies do report differences in the amplitude of the waveform evoked in the congruent relative to the incongruent condition (Aine and Harter, 1984; Liotti et al., 2000; Rebai et al., 1997; Shack et al., 1999; West and Alain, 1999), most often around the 300–450 ms post stimulus onset time window, thus supporting "early selection" theories. Early selection accounts view the conflict as originating at the encoding stage, where the perceptual encoding of the ink-colour information is slowed by the colour-word information (MacLeod, 1991). The majority of ERP studies report a frontal or fronto-central negative wave that is systematically related to manipulations of Stroop conditions (Aine and Harter, 1984; Liotti et al., 2000; Rebai et al., 1997; Shack et al., 1999; West and Alain, 1999). This is consistent with an assumed frontal site of generation, and is in agreement with fMRI and PET research as reviewed above.

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