Research Report

Electrophysiological measures of conflict detection and resolution in the Stroop task

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ARTICLE INFO

ABSTRACT

Conflict detection and resolution is crucial in a cognitive task like the Stroop task. Previous studies have identified an early negativity component (N_{inc}) as a prominent marker of Stroop conflict in event-related potentials (ERPs). However, to what extent this ERP component reflects conflict detection and/or resolution is still unclear. Here, we report a Stroop task in which the stimulus onset asynchrony (SOA) of color and word stimuli presentation was manipulated in order to disentangle the roles of conflict detection and conflict resolution in generating Stroop-related ERP components. Separating the word from the color information gives us precise control over the timing of conflict. If the N_{inc} is related with conflict resolution it should be absent when the word appears during response preparation, as in a long-latency positive SOA. Our data shows that the N_{inc} occurs in all SOAs, even after a response has been made, supporting its role in the detection of stimulus conflict rather than conflict resolution. The use of SOA manipulation therefore allows for the examination of a wider temporal spectrum of interference in order to specify the functions of this conflict-related component. These results provide insight into the neural signatures of conflict processes, and have implications for models of cognitive control mechanisms in the brain.

1. Introduction

A key feature of the human cognitive system is the implementation of executive control, abilities which include attending to relevant information, goal and input control, and overcoming conflict. The Stroop task is a prominent measure of cognitive conflict and executive control in the field of cognitive psychology. In a color-naming Stroop task, color words are presented in colored ink, and participants are asked to ignore the printed word and instead name the color of the ink, a task which requires inhibition of the highly practiced reading process. In incongruent conditions (in which the word and ink color do not match; e.g. 'blue' printed in green ink), the conflicting word and color information requires cognitive control and conflict resolution processes to be engaged, leading to a delay in reaction time (RT) as compared to congruent conditions (in which the word and color match) or control conditions (typically a non-linguistic or non-response set stimulus printed in colored ink; e.g. 'xxxx' printed in blue). The longer RT in an incongruent condition compared to a congruent condition is known as the Stroop Effect.

Functional magnetic resonance imaging (fMRI; e.g. Peterson et al., 1999), positron emission tomography (PET; e.g. Taylor et al., 1997), and electroencephalography (EEG; e.g. Aine and Harter, 1984; Markela-Lerenc et al., 2004) research has found that the anterior cingulate cortex (ACC) is activated during the Stroop and other conflict tasks. This brain region is thought to be one of the primary hubs for executive control processes such as conflict monitoring, detection and resolution (Melcher and Gruber, 2009; Peterson et al., 1999; Peterson et al., 2002). EEG research has identified a prominent Stroop-related ERP component sensitive to congruency manipulations: an early component, referred to here as a negativity associated with the incongruent condition (N_{inc}).

The N_{inc}, often referred to as an N450, is identified as a more negative wave in the incongruent condition as compared to either the congruent or control conditions, appearing from approximately 300 to 550 ms post-stimulus over left centro-parietal scalp (Appelbaum et al., 2009; Larson et al., 2009; Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003). Source localization techniques have traced this component to the prefrontal cortex, specifically the ACC (Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000), and the general consensus in the literature is that this component is related to processes of conflict detection and resolution which are more active in the incongruent condition. However, previous EEG research has not yet distinguished between the processes of conflict detection or resolution involved in generating the N_{inc}. While it has been suggested by some that the N_{inc} reflects the detection of interference originating from the ACC (Hanslmayr et al., 2008; West, 2003), this component has been under-specified in the literature. The overall conclusion so far is that the N_{inc} reflects general conflict detection and resolution processes, most likely arising from the ACC.

One important variation of the Stroop task involves manipulation of stimulus onset asynchrony (SOA: Dyer, 1971; Glaser and Glaser, 1982), which presents the color and word stimuli at different times in order to investigate the precise timing of color and word interference. A series of seminal experiments by Glaser and Glaser (1982) included nine SOAs from −400 ms to +400 ms in 100 ms intervals. Negative SOAs present the irrelevant (word) stimulus before the relevant (color) stimulus, with inter-stimulus intervals determined by the specific SOA. Positive SOAs present the irrelevant stimulus after the relevant stimulus. A 0 ms SOA presents the stimuli simultaneously, as in a traditional Stroop task. Glaser and Glaser (1982) reported the most inhibition (calculated as incongruent RT minus control RT) at 0 and ±100 ms, with diminishing but still significant amounts of inhibition out to −400 ms. Facilitation (control RT minus congruent RT) was not present at 0 ms but increased with longer negative SOAs. In positive SOAs, both inhibition and facilitation were present to +200 ms, but all effects were gone by later SOAs, indicating that the irrelevant word appears too late to have any influence on color naming at long positive SOA latencies.

The goal of the current study is to determine whether conflict detection or conflict resolution is generating the N_{inc}. To disentangle these two cognitive processes we employ long-latency SOAs (−400 ms and +400 ms) as well as a 0 ms SOA. In the −400 ms and 0 ms SOAs we expect to see an N_{inc}; but these SOAs cannot clarify whether the N_{inc} is due to conflict detection and/or conflict resolution. Behavioral studies with

a manual SOA Stroop task (Coderre et al., Submitted; Glaser and Glaser, 1982) have shown that RTs in the +400 ms SOA occur at approximately 500 ms. This means that a response is already being prepared or executed at the moment the word appears (400 ms after the color). Thus, if the N_{inc} reflects conflict detection, it should be present in the +400 ms SOA because conflict is still present in the incongruent condition even if a response has already been made. If the N_{inc} reflects conflict resolution, it should be absent in this SOA as a response has been made and no resolution is necessary. The use of SOA manipulation thus provides a unique opportunity to clarify the function of this component.

A second Stroop-related ERP component is sometimes reported as being related to conflict processing: a late positive component (LPC), sometimes called a slow positivity (SP: Chen and Melara, 2009) or a conflict slow potential (conflict SP: Larson et al., 2009; West, 2003). It is identified as a more positive wave in the incongruent condition than the congruent or control conditions, occurring from approximately 600 to 900 ms post-stimulus over centro-parietal scalp (Appelbaum et al., 2009; Larson et al., 2009; Liotti et al., 2000; West and Alain, 1999). The cognitive processes underlying this component are even more ambiguous in the literature than the N_{inc}, being attributed to a broad array of cognitive functions. One study traced the LPC to the middle or inferior frontal gyrus and left extrastriate region (West, 2003), implicating its role in conflict resolution processes. In contrast, the amplitude of the LPC was found to be correlated with RT and accuracy, suggesting that this component is involved not in conflict resolution but in response selection (West et al., 2005). Overall, it appears that the LPC is somehow involved in conflict processing, but it has alternatively been suggested that the LPC reflects semantic processing (Appelbaum et al., 2009; Liotti et al., 2000) given its source localization to Wernicke's area (Snyder et al., 1995). Specifically, it may be associated with semantic re-activation of the word following signaling of conflict resolution from anterior regions of the brain such as the ACC (Liotti et al., 2000). Thus though it is frequently reported in Stroop ERP studies, the underlying cognitive processes involved in generating the LPC remain unclear.

One previous study (Appelbaum et al., 2009) has investigated SOA manipulation in the Stroop task with EEG. This study used five SOAs of ±200, ±100 and 0 ms while recording concurrent EEG. In the 0 ms SOA an N_{inc} was identified from 300 to 500 ms and an LPC from 750 to 900 ms. These components were modulated by SOA manipulation: in the −100 ms SOA, the N_{inc} and LPC were shifted forward (i.e. appeared earlier) by 100 ms as compared to the 0 ms SOA; in the −200 ms SOA both were shifted forward by 200 ms. These results indicate that at short negative SOAs, there is a linearity in these component shifts. Appelbaum et al., (2009) also report that in both the +100 and +200 ms SOAs the N_{inc} peaked 100 ms after the 0 ms SOA, and the LPC was also shifted 'backwards' (appeared later) by 100 ms in the +100 ms SOA. This backwards shift appears when the ERP signal is time-locked to the target color stimulus, as is traditional in Stroop ERP studies. However, as these are conflict-related components, and in light of the temporal manipulation, time-locking to the second stimulus presented (i.e. the word in the positive SOAs) provides a better reflection of exact timing of conflict processes, as conflict does not occur until presentation

of the second stimulus. If one re-interprets the results of Appelbaum et al., (2009) this way, then the onsets of the N_{inc} and LPC do not occur later in the positive SOAs, but rather at similar latencies as in the 0 ms SOA. In addition, Appelbaum et al., (2009) report that the LPC was absent in the +200 ms SOA, which was interpreted as a lack of semantic activation at this latency since the word appears too late to cause any interference. The work of Appelbaum et al., (Submitted) therefore indicates that at early negative SOAs there is a linear modulation of component latency, but at positive SOAs this linear shift disappears. The current study seeks not only to specify the underlying cognitive processes associated with the N_{inc}, but also to establish the time limits of these conflict-related cognitive processes by investigating whether long-latency negative SOAs also produce linear latency shifts. Based on the findings of Appelbaum et al., (2009), we expect that the −400 ms SOA will show an N_{inc} and an LPC that occur significantly earlier than in the 0 ms SOA. If the N_{inc} and LPC are linearly shifted by SOA manipulation, they should occur 400 ms earlier in the −400 ms SOA than in the 0 ms SOA. In the +400 ms SOA, it is expected that an N_{inc} will occur at the same time as the 0 ms SOA, and an LPC will be absent.

In accordance with traditional Stroop terminology, we define *Stroop effects* as incongruent vs. congruent conditions (incongruent RT minus congruent RT in behavioral data and a comparison of these waveforms in the ERP data); *inhibition effects* as the incongruent vs. control conditions; and *facilitation effects* as the control vs. congruent conditions. *Interference effects* here refer more generally to either Stroop or inhibition effects.

2. Results

2.1. Behavioral results

Behavioral RTs for the congruent, control and incongruent conditions, and the magnitudes of the Stroop, inhibition and facilitation effects in each SOA, are presented in Table 1. A 3 (SOA) × 3 (congruency) repeated-measures ANOVA showed a significant main effect of SOA ($F(2,60) = 8.55$, $p < 0.01$), a significant main effect of congruency ($F(2, 60) = 69.36$, $p < 0.001$), and an interaction of SOA and congruency ($F(4,120) = 30.21$, $p < 0.001$). Paired-sample t-tests were conducted to identify significant Stroop, inhibition and facilitation effects. Significant Stroop effects occurred at −400 ms ($t(30) = 10.11$, $p < 0.001$) and at 0 ms ($t(30) = 8.30$, $p < 0.001$). Significant inhibition occurred at 0 ms ($t(30) = 6.78$, $p < 0.001$) and −400 ms ($t(30) = 4.32$, $p < 0.01$). Significant facilitation occurred at −400 ms ($t(30) = 9.56$, $p < 0.001$) only. No Stroop, inhibition, facilitation effects occurred at the +400 ms SOA.

2.2. ERP results

In the 0 ms SOA, an N_{inc} was present from approximately 400 to 500 ms over centro-parietal scalp (Fig. 1a and Fig. S1 in the Supplementary material). Within this N_{inc} window, significant effects were found for the Stroop comparison at Cz, P3, Pz and P4, and for the inhibition comparison at C3, Cz, C4, P3, Pz and P4. A brief window of significance was found in the facilitation comparison at P4. An LPC was also observed in the 0 ms SOA from approximately 600 to 900 ms over centro-parietal scalp. Significance in the Stroop comparison was found at Cz, P3 and Pz; in the inhibition comparison at Cz, C3, C4, P3, Pz and P4; and in the facilitation comparison (control more positive than congruent) at F3, Fz, F4, and Cz. As the 0 ms SOA here is similar to a traditional Stroop task, this replicates the previous findings of Stroop-related ERP components (Appelbaum et al., 2009; Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Larson et al., 2009; Liotti et al., 2000; Markela-Lerenc et al., 2004; West and Alain, 1999).

In the −400 ms SOA, an N_{inc} was found over centro-parietal scalp from approximately 200 to 350 ms after color presentation (Fig. 1b and Fig. S2). Within this N_{inc} window, the Stroop comparison showed a significant difference at Cz, C4, P3, Pz and P4. The inhibition comparison showed significance at Cz, P3 and Pz. The facilitation comparison showed significance (control more negative than congruent) at Cz, C4, P3, Pz and P4. An LPC was also identified in this SOA over centro-parietal scalp from approximately 400 to 600 ms after color presentation (Fig. 1b). Within this LPC window, the Stroop comparison showed significance at Cz, P3, Pz and P4; the inhibition comparison yielded no significant differences except for a very small window of significance at P4; and the facilitation comparison showed significance at C3, Cz, P3, Pz and P4.

The latency of the N_{inc} in the −400 ms SOA was compared to the N_{inc} in the 0 ms SOA by performing a latency analysis. Significant differences in the latencies of the N_{inc} occurred at all electrodes such that the N_{inc} occurred earlier in the −400 ms SOA (average N_{inc} latency across all conditions at Pz: 0 ms = 471 ms; −400 ms = 233 ms; total forward shift of 238 ms). A latency analysis of the LPC in the −400 ms SOA compared to the 0 ms SOA also indicated a significant forward shift such that the LPC occurred earlier in the −400 ms SOA (average LPC latency across all conditions at Pz: 0 ms SOA = 653 ms; −400 ms SOA = 440 ms; total forward shift of 213 ms). The forward latency shift of these components in the negative SOA is consistent with previous literature (Appelbaum et al., 2009) and with our predictions. However, the latency shift of these components was approximately 200 ms; but if the SOA manipulation linearly shifted these components forward we should have observed a forward shift of 400 ms. Thus our findings indicate that these

Table 1 – Behavioral RT data: mean reaction times for the congruent, control and incongruent conditions, and magnitudes of the Stroop (incongruent–congruent), inhibition (incongruent–control) and facilitation (control–congruent) effects in msec. Standard errors (SE) are reported in parentheses.

SOA	Congruent	Control	Incongruent	Stroop effect	Inhibition effect	Facilitation effect
−400	544 (13)	611 (16)	642 (17)	99 (10)	31 (7)	68 (7)
0	592 (15)	592 (15)	661 (20)	69 (8)	69 (10)	0 (5)
400	638 (20)	645 (21)	656 (23)	18 (7)	11 (7)	6 (5)

components are not linearly shifted at long-latency SOAs, which will be taken up in the Discussion.

In the +400 ms SOA, latency analyses considered the ERPs as being time-locked to the word rather than the target (color) stimulus, as discussed in the Introduction. An N_{inc} was observed over left central electrodes from approximately 300 to 450 ms after word onset (700 to 850 ms after color onset; Fig. 1c and Fig. S3). The N_{inc} window showed significant Stroop differences at Cz, P3 and Pz; significant inhibition differences at C3, Cz and P3, and significant facilitation differences at C4, Pz and P4 (control more positive than congruent). When time-locked to the word stimulus, the latency of the N_{inc} in the +400 ms SOA was not significantly different than that of the 0 ms SOA (average N_{inc} peak latency across all conditions at Pz: 0 ms SOA = 471 ms; +400 ms SOA = 417 ms), which supports our predictions. No LPC was found in the +400 ms SOA, as was predicted.

The finding of an N_{inc} in such a long-latency positive SOA is significant for our interpretation of the N_{inc} as being involved in either conflict detection or conflict resolution. Within the entire trial, the N_{inc} appeared from 700 to 850 ms after the target (color) stimulus was presented. The median response time across all congruencies for the +400 ms SOA is 597 ms, meaning that when the N_{inc} appears at 700 ms a response has generally already been made. This suggests that the N_{inc} is not related to conflict resolution, as resolution has already occurred in order to produce a correct response. To investigate this claim that the N_{inc} occurs after response generation, we divided the data into fast- and slow-RT trials by performing a median split over all trials for all subjects in the +400 ms SOA (median RT = 597 ms). We focused on an N_{inc} window based on the overall findings in the +400 ms SOA (700 to 850 ms). Within this window, the incongruent condition was more negative than the congruent condition at Cz and Pz in both the fast and slow RT trials (see Fig. S4). Running t-tests performed within this window in the fast RT trials identified a significant Stroop effect from approximately 750 to 780 ms at Pz, as well as inhibition at P4. In the slow RT trials, a significant Stroop effect was found from approximately 710 to 780 ms, as well as inhibition at C3 and P3, and facilitation at P3 and P4. Therefore an N_{inc} occurred in both the fast and slow RT trials, despite the fact that the effects were weakened due to reduced power from halving the number of trials in each comparison.[1] Crucially, in the fast-RT trials, all behavioral responses were completed by 600 ms; and yet a significant N_{inc} appears at approximately 750 ms, long after a response has been made. This suggests that the N_{inc} reflects processes of

conflict detection, rather than conflict resolution, which we will examine further in the Discussion.

3.   Discussion

The current study used a long-latency SOA manipulation in a Stroop task with EEG to investigate the contribution of conflict detection and resolution processes in generating the N_{inc} and LPC components. Behaviorally, we replicated the results of previous Stroop SOA studies (Coderre et al., submitted; Glaser and Glaser, 1982) in finding peak interference effects at 0 ms SOA with less, but still significant, inhibition at −400 ms, increased Stroop and facilitation effects at −400 ms SOA, and no effects at +400 ms SOA. The EEG data revealed an N_{inc} and an LPC in the 0 ms SOA, which replicates the results of previous Stroop ERP studies (Appelbaum et al., 2009; Badzakova-Trajkov et al., 2009; Hanslmayr et al., 2008; Liotti et al., 2000; Markela-Lerenc et al., 2004; West and Alain, 1999). An N_{inc} and an LPC also appeared in the −400 ms SOA but both appeared significantly earlier than in the 0 ms SOA. Thus as predicted, Stroop-related ERP components are shifted forward in time in negative SOAs. The +400 ms SOA exhibited an N_{inc} but not an LPC. Importantly, it is this positive SOA that is the most critical in determining the role of the N_{inc} in Stroop conflict.

The +400 ms SOA elicited an N_{inc} from 300 to 450 ms after word presentation, which is not a significant latency shift compared to the 0 ms SOA. Within the entire trial, however, the N_{inc} appeared from 700 to 850 ms after the target (color) stimulus was presented, which is after the median response time of 597 ms. Moreover, our post-hoc split of the data into fast and slow RT trials indicated that an N_{inc} was present in both groups, including the fast-RT trials when all responses were completed by the time the N_{inc} appeared. These results indicate that the N_{inc} is not related to conflict resolution, as resolution has already occurred in order to produce a correct response, but rather is reflective of conflict detection processes (Hanslmayr et al., 2008; West, 2003) which are ongoing and continue after response generation. When the relevant color dimension is pre-exposed in the +400 ms SOA, a response can be selected and prepared without interference. When the word appears 400 ms later, a response is already in preparation, but the presence of an incongruent word still triggers a 'mismatch' response in the brain, initiating conflict detection processes and generating an N_{inc}.[2]

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[1] We also compared the fast and slow RT trials by computing the average amplitude over the N_{inc} window from 700 to 850 ms in all conditions. In the fast RT trials at Cz, there were no significant differences (all p's > 0.29). At Pz, there was a strong trend towards a significant difference between the incongruent and congruent conditions (t(30) = 2.01, p = 0.05), but no other differences (all p's > 0.12). In the slow RT trials at Cz, there was a significant difference between the incongruent and congruent conditions (t(30) = 2.52, p < 0.05), but no other differences (all p's > 0.10). At Pz, there was a strong trend towards a significant difference between the incongruent and congruent conditions (t(30) = 1.94, p = 0.06), but no other differences (all p's > 0.33). Therefore the average amplitude also confirms that there is an N_{inc} present at Pz in the fast RT trials and at Cz in the slow RT trials. The topographical differences between the trial types are likely an effect of the reduced power resulting from splitting the data.

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[2] It is possible in the +400 ms SOA that the N_{inc} is reflecting additional regulatory aspects of conflict processing beyond just conflict detection. For example, the presentation of an incongruent word even after a response has been made may trigger not just conflict detection processes but also regulatory processes like response inhibition (West & Alain, 2000) or selective enhancement of the goal concept (Roelofs et al., 2006). While it is possible that these processes are also triggered upon presentation of an irrelevant word, it may be that they are not carried out to full completion, since maintenance of task goals should realize that the target has been identified already and a response has been made, therefore regulatory processes are no longer needed. Therefore it is possible that the N_{inc} in the +400 ms SOA also reflects aspects of conflict resolution, however, we believe that the most parsimonious explanation of this component in this SOA is that it reflects conflict detection processes, which are ongoing and continue after response selection.

Other ERP literature has also found that conflict detection processes are ongoing: for example, the error-related negativity (ERN) is an enhanced negativity component, which appears shortly after an incorrect response has been made (e.g. Falkenstein et al., 2000; Ullsperger and von Cramon, 2006). It is thought that the ERN reflects a signaling of conflict between the response made and the correct response (Yeung et al., 2004); it is therefore essentially a conflict detection component. As the ERN literature demonstrates, conflict monitoring occurs after a response has been made, and signaling of conflict can occur after response generation, which is in line with the current findings.

Rather than being conflict-specific, the N_{inc} could reflect a more general 'mismatch' detection. Because the control condition is not a part of the response set, an 'xxxx' stimulus may trigger the same types of non-match responses as the conflicting incongruent stimulus. However, both the 0 ms and +400 ms SOA show significant differences in the Stroop and inhibition comparisons, but not in the facilitation comparisons, at the N_{inc} window, meaning that the congruent and control conditions are behaving similarly while the incongruent condition differs. This suggests that the N_{inc} in fact reflects conflict detection due to the semantic incongruency between the word and color, rather than detection of response set mismatch in both the incongruent and control conditions.

As mentioned, the N_{inc} has been traced using source localization to the ACC, which is a prominent structure involved in conflict though debates exist about its precise role in cognitive control. Two of the most prominent theories of ACC function are the conflict monitoring hypothesis and the regulative hypothesis. The conflict monitoring hypothesis (Botvinick et al., 2001) states that instead of having a hands-on role in conflict resolution, the ACC merely monitors for and assesses the degree of incoming conflict. It then signals other regulative networks, including areas of the prefrontal cortex such as the dorsolateral prefrontal cortex (DLPFC) to help resolve the conflict (Botvinick et al., 2001; Botvinick et al., 2004). Conflict monitoring involves not just detecting mismatching stimuli but additional processes such as maintenance of task goals (e.g. Roelofs, 2003; Dosenbach et al., 2007). Thus if the N_{inc} arises from activation of the ACC during conflict monitoring, it may also reflect additional working memory processes such as remembering that the color is the target stimulus and the word is irrelevant. In contrast, the regulative hypothesis of ACC function suggests that the ACC exerts top–down regulation of response selection processes, for example by enhancing the activation of the goal concept until a selection threshold is exceeded (Roelofs et al., 2006). This view therefore implicates the ACC in conflict resolution.

These theories are difficult to reconcile in light of the current data. Simulations of the conflict monitoring view predict increased ACC activity for the incongruent condition but an equal amount of activation for neutral and congruent trials, since there is no conflict present in either of the latter conditions (Botvinick et al., 2001; Roelofs et al., 2006). This is what our data shows in the 0 ms SOA: in the N_{inc} window, the incongruent condition is most negative but the control and congruent waveforms behave similarly. In contrast, the regulative view of ACC function predicts that the incongruent condition should have the most activity, followed by the control and congruent,

respectively: that is, less regulation of control is needed for congruent trials than control trials since the correct response has already been activated by the distractor word. This is what we see in the −400 ms SOA: within the N_{inc} window, the incongruent condition is the most negative, followed by the control and congruent, respectively. The +400 ms SOA is less clear: at the N_{inc} window there are Stroop and facilitation effects, indicating that the incongruent and control condition are behaving similarly, which does not support either hypothesis. It may be that the N_{inc} is reflecting slightly different conflict processes in each SOA. For example, in the −400 ms and 0 ms SOAs, the N_{inc} could reflect both conflict detection and resolution processes, whereas in the +400 ms SOA it reflects mainly conflict detection. Another possibility is that due to the poor spatial resolution of EEG, activity from different regions of the prefrontal control network, or even different parts of the ACC, are being picked up in the N_{inc} component in each SOA. It has also been shown that different ACC sub-regions perform different functions (e.g. Peterson et al., 1999; van Veen and Carter, 2005) and even respond to different types of conflict (Kim et al., 2011). It is evident that the role of this structure in conflict processing is complex, therefore concrete conclusions on the ACC's role in the SOA-modulated Stroop task, and on the ERP components that may arise from its activation, require further neuroimaging evidence.

In the −400 ms SOA, the pre-exposure of the word creates a semantic priming effect that can explain the behavioral and ERP data. Pre-exposure of the irrelevant word initiates lexical and semantic activation which allows conflict detection processes to get a 'head-start' when the color stimulus is subsequently presented: the meaning of the word has already been accessed, so evaluation of the degree of conflict can occur more quickly. This explains why an N_{inc} occurs earlier in the −400 ms SOA. It also explains the increased behavioral facilitation and Stroop effects in the −400 ms SOA which are driven by a faster RT in the congruent condition. In congruent conditions, pre-activation of the word creates a semantic priming effect such that the concept of the color is already activated when the color appears, allowing response selection processes to occur more quickly. In the 0 ms SOA, when the color and word are presented simultaneously, the lexical properties of the word must first be accessed, a process which takes up to 200 ms (Pulvermüller et al., 2001), before conflict processes can be initiated. In the +400 ms SOA, when the word is post-exposed, conflict detection is again limited by the time needed for semantic access, explaining the similar N_{inc} latencies between the +400 ms and 0 ms SOAs. Conflict processes in the Stroop task are thus heavily reliant on the speed of lexical access, which must fully occur before conflict detection and subsequent resolution can take place.

We turn now to a discussion of the second Stroop-related ERP component, the LPC. While it can only be offered as a speculative conclusion, the current results suggest that this component is involved in conflict resolution processes. As mentioned earlier, the cognitive generator of the LPC is unspecified. The LPC has been implicated by some in semantic re-activation following conflict resolution (Appelbaum et al., 2009; Liotti et al., 2000), as well as more generally in conflict resolution processes (Chen and Melara, 2009; Larson et al., 2009; West, 2003). In the current data, an LPC is observed in the 0 ms and −400 ms SOAs when resolution is needed and large
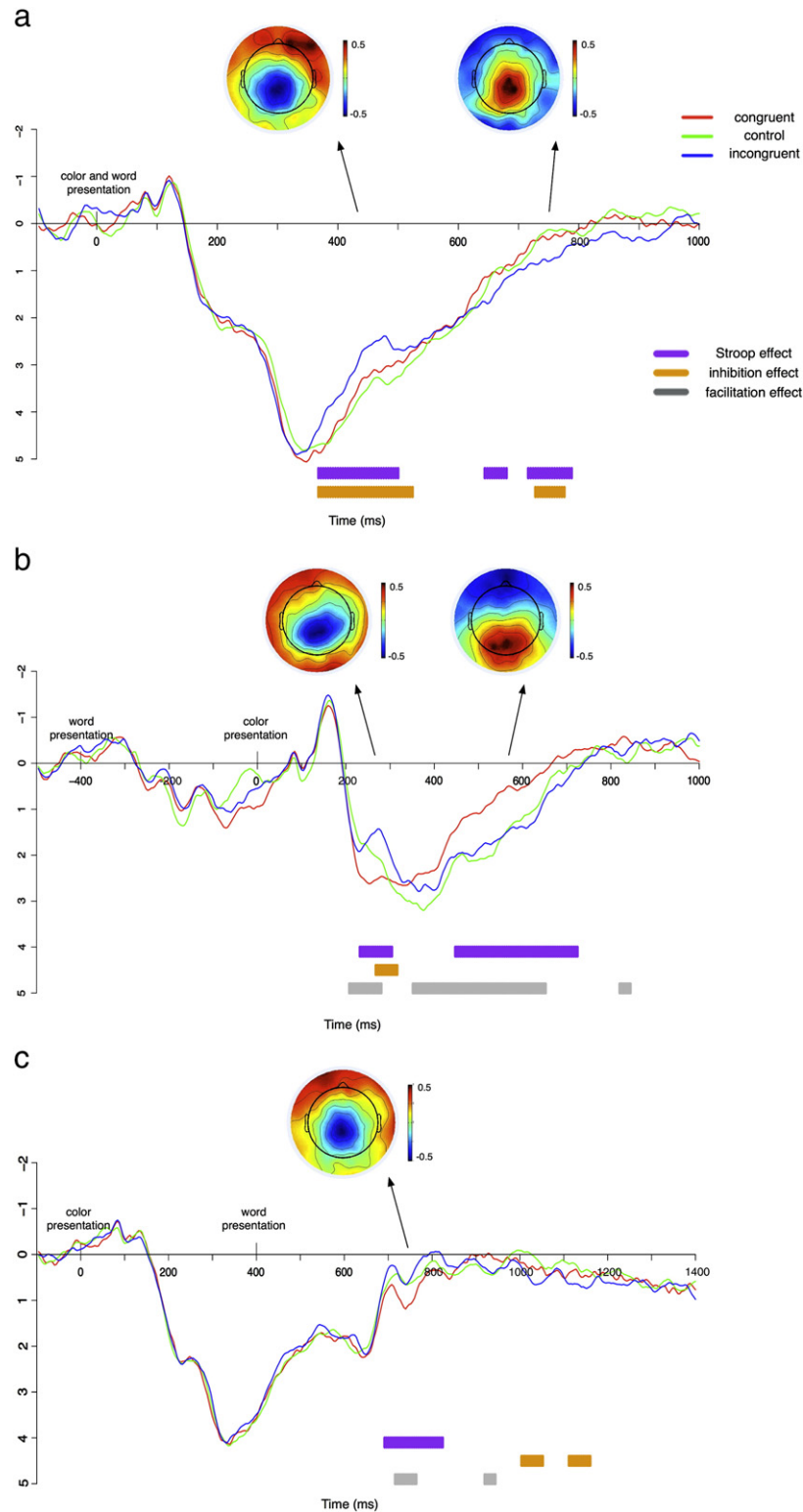
Fig. 1 – ERP waveforms at electrode Pz for the a) 0 ms SOA; b) −400 ms SOA; and c) +400 ms SOA. Congruent (red), control (green) and incongruent (blue) waveforms are presented, with significant effects within the pre-defined N_{inc} windows (300 to 600 ms for 0 ms SOA; 100 to 600 ms for −400 ms SOA; 300 to 800 ms for +400 ms SOA) and LPC windows (600 to 900 ms for 0 ms SOA; 400 to 900 ms for −400 ms SOA; 600 to 1100 ms for +400 ms SOA), as based on running *t*-tests, indicated in bars underneath. Significance is plotted for the Stroop (purple: incongruent vs. congruent), inhibition (orange: incongruent vs. control) and facilitation (gray: control vs. congruent) comparisons. Topographic maps of the incongruent–congruent differences are shown at the N_{inc} and LPC latencies (where applicable), taken at the approximate middle of the significant window (0 ms SOA: 425 ms and 750 ms; −400 ms SOA: 275 ms and 575 ms; +400 ms SOA: 750 ms).

behavioral interference effects occur, but it is absent in the +400 ms SOA where conflict resolution is not needed because of the late arrival of the color word, as is further supported by the lack of behavioral interference effects. In the 0 ms SOA the LPC arises after a response has been made, which rules it out as being directly involved in conflict resolution and instead suggests that this component is somehow involved in post-conflict resolution processing. It may be that these post-resolution processes include a re-activation of the semantic information which was initially suppressed to overcome conflict (Liotti et al., 2000) and/or a general lifting of other cognitive control processes (Larson et al., 2009).

However, in the −400 ms SOA, the LPC occurs during the average response time (median RT for all −400 ms SOA trials=558 ms; incongruent median=594; control=567; congruent=503 ms), suggesting that perhaps this component is involved in conflict resolution itself, such as the implementation of resolution processes. It has been found that conflict resolution processes function by enhancing processing of task-relevant information (Egner and Hirsch, 2005). In the −400 ms SOA, Stroop and facilitation effects but not inhibition effects occur, indicating that the incongruent and control conditions are behaving similarly (see Fig. 1). This finding can be explained by assuming that pre-exposure of the word in the −400 ms SOA leads to activation of a 'concept node' (see WEAVER++ model, Roelofs, 2003) related to the semantics of the word (except in the control condition). When the color (i.e. target stimulus) is subsequently presented, a new concept node must be activated. In the congruent condition, the relevant concept node has already been pre-activated by the word, requiring no conflict resolution. However, in the incongruent and control conditions a different concept node will be activated by the color (target stimulus). As the color is the task-relevant stimulus, conflict resolution processes enhance attention to the second stimulus in order to activate the correct concept node to produce a correct answer. Thus, if the LPC does reflect conflict resolution processes, it may explain why similar LPC patterns occur in the −400 ms SOA incongruent and control conditions but not the congruent conditions (therefore the LPC appears in Stroop and inhibition effects but not in facilitation effects). This explanation implicates the LPC in conflict resolution directly, rather than post-resolution processes. However, as mentioned in the Introduction, the literature on the LPC is somewhat vague, and unfortunately no concrete conclusions can be made from the current data on this component. We conclude only that the LPC appears to be involved in conflict resolution processes; whether it is directly involved, or signals a post-resolution effect, requires further research.

The current study also investigated whether the latency offsets of the N_{inc} and LPC in negative SOAs remain linear at long-latency SOAs such as −400 ms. Our results clearly show that this is not the case. The forward shift for both the N_{inc} and LPC components in the −400 ms SOA was only approximately 200 ms, a similar offset to the −200 ms SOA found in an earlier study (Appelbaum et al., 2009), whereas a linear shift would predict these components to occur 400 ms earlier than in the 0 ms SOA. Full semantic activation has been found to occur within 200 ms (Pulvermüller et al., 2001), so this 200-ms latency shift indicates that any pre-exposure of the word

longer than this time window of semantic access has no additional effect on subsequent conflict processing. This explains why previous behavioral SOA studies (Coderre et al., submitted; Glaser and Glaser, 1982) and model simulations of the SOA Stroop task (Roelofs, 2003) show relatively stable amounts of inhibition and facilitation beyond −200 ms, since after the word is fully activated, any additional pre-exposure results in a plateau of priming effects.

In sum, the current study identified two electrophysiological components reflecting conflict detection and resolution processes in the brain, and the use of SOA manipulation has allowed us to specify the cognitive processes associated with these components. Our data shows that the N_{inc} component is indicative of conflict detection processes. In contrast, the LPC is related to conflict resolution processes rather than conflict detection processes, though what precise role it plays in conflict resolution is unclear. Thus by examining a wider temporal spectrum of interference we are able to disambiguate the function of prominent but previously underspecified ERP components and more fully investigate the time course of conflict mechanisms in the brain.

4.   Experimental procedure

4.1.   Participants

Participants were 31 native English speakers from the University of Nottingham (18 female; mean age=22 years, SD=5.1). All were right-handed, reported no color-blindness or history of neurological disease, and had normal or corrected-to-normal vision.

4.2.   Design and materials

Word stimuli were the words 'red', 'green', and 'blue' in lowercase font. Control word stimuli consisted of 'xxxx'; this was included as a non-word, non-color control condition. Color stimuli consisted of red, green and blue filled rectangles (284×142 pixels) with a smaller black-filled rectangle centered inside (142×42 pixels). Word stimuli were presented in white ink centered inside the black rectangle. Congruent stimuli presented the same word and color (e.g. 'red' surrounded by a red rectangle). Incongruent stimuli presented non-matching words and colors (e.g. 'green' surrounded by a blue rectangle). Control stimuli presented 'xxxx' surrounded by red, green or blue rectangles. Participants were asked to ignore the word and respond to the color of the rectangle by pressing a corresponding button on the keyboard. The buttons were not labeled, but the participants were instructed that the right index finger was to be used for red, right middle finger for green and right ring finger for blue. Participants were given a practice session to familiarize themselves with the mappings.

4.3.   Procedure

Ethics approval was granted by the Research Ethics Committee in the School of Psychology at the University of Nottingham. Informed consent was obtained from all participants prior to experimental testing. Participants were tested in one session of approximately 1.5 h, including EEG net application

and set-up. Participants were first given a brief practice session with only color stimuli, followed by the experimental session which was approximately 50 min long.

E-Prime was used to present the stimuli and collect behavioral data. The entire experimental session consisted of twelve blocks of approximately 4 min each. Three SOAs were used: −400, 0, and +400 ms. SOA was blocked (four blocks per SOA) and counterbalanced across participants, and congruency was randomized within blocks. Each SOA consisted of 216 trials, of which 72 were congruent, 72 control and 72 incongruent, resulting in 648 trials total. In each trial, a fixation cross appeared for 500 ms, followed by a blank screen for 300 ms, and then the word and/or color stimuli appeared. In the −400 ms SOA, the word appeared on the screen for 400 ms and then was surrounded by the colored rectangle. In the +400 ms SOA, the colored rectangle appeared for 400 ms, and then the word appeared in the center of the rectangle. In the 0 ms SOA, both word and color stimuli appeared at the same time. Once both stimuli were presented they remained on the screen for 1000 ms. Participants were instructed to respond to the color of the rectangle as quickly and accurately as possible. A blank screen was presented following each trial at an interstimulus interval (ISI) varying from 1500 to 2000 ms.

4.4. Data acquisition

High-density ERPs were recorded at 250 Hz using a Geodesics 128-channel sensor net and NetStation version 4.3. Where possible, impedances were kept under 50 kΩ before recording began. Data was preprocessed using EEGlab version 6.0 and Matlab version 7.9. The data was filtered using a 0.5–40 Hz bandpass filter and transformed using an average reference transform. Eye movement artifacts were corrected for by first running principal component analysis (PCA) on each participant to identify the number of components required to explain 99% of the data. Independent component analysis (ICA) was then run using the specified number of components. Eye movements, blinks and other noise components were identified and removed from the data. The cleaned continuous data was segmented into epochs which were time-locked to the onset of the color stimulus. For the −400 ms SOA, segments extended from 500 ms before to 1000 ms after the color stimulus in order to include the response to the word (presented at −400 ms). For the 0 ms SOA, segments extended from 100 ms before to 1000 ms after stimuli presentation. For the +400 ms SOA, segments extended from 100 ms before to 1400 ms after the color stimulus in order to include the response to the word (presented at +400 ms). Each segment was baseline corrected using data from the first 100 ms of the segment. Additional bad epochs were identified and rejected using a joint probability computation. The average number of trials retained per participant was 93%. An average of 2074 trials per condition was included in the analysis.

4.5. Data analysis

4.5.1. Behavioral data
Incorrect trials were removed from the behavioral data (3.4% of total trials). Because this error rate is so low, an error analysis was not performed. Trials with RTs of less than 250 ms or greater than 2000 ms were deemed outliers and also omitted from the data, resulting in an additional 0.12% of the data being removed. The reported p-values for paired-sample t-tests are all Bonferroni-corrected.

4.5.2. ERP data
As mentioned, the previous literature defines the N_{inc} within a window from approximately 300 to 600 ms, and the LPC from 600 to 900 ms. We therefore restricted our analyses of these components to these pre-specified time windows for the 0 ms SOA. However, as was demonstrated by Appelbaum et al. (2009), these components may be shifted by SOA manipulation, so different windows were specified for the −400 and +400 ms SOAs. In the −400 ms SOA, the analysis windows were defined as the traditional window plus a 200-ms negative shift, making an N_{inc} analysis window from 100 to 600 ms and an LPC analysis window from 400 to 900 ms after presentation of the color stimulus. For the +400 ms SOA, the analysis window allowed for a 200-ms backwards shift, making an N_{inc} analysis window from 300 to 800 ms and an LPC window from 600 to 1100 ms post-stimulus.

The ERP data was compared using running t-tests within analysis windows (100 to 900 ms post-stimulus). The raw data was averaged into bins of 20 ms, with an overlap of 12 ms. Within each bin, the average voltage value was computed and paired-samples t-tests were performed between each condition. Significant windows ($p < 0.05$) reported for nine major electrode sites across the scalp (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). Reported window onsets indicate the approximate start of the significant window based on the running t-tests. Graphs of the nine major electrode sites can be found in the Supplementary material. Fig. 1 presents the waveforms at Pz. All graphs only present significant windows of running t-tests within the analysis windows.

Latency analyses were performed between SOAs by identifying the bin containing the minimum amplitude (indicating the most negative peak) within the N_{inc} window, or the maximum amplitude (the most positive peak) within the LPC window, at every electrode for each SOA and compared using a paired-samples t-tests and Bonferroni-corrected p-values. The N_{inc} windows for each SOA were: 0 ms SOA, 400 to 500 ms; −400 ms SOA, 200 to 350 ms; +400 ms SOA: 300 to 500 ms. The LPC windows were: 0 ms SOA, 600 to 900 ms; −400 ms SOA, 400 to 600 ms.

Supplementary materials related to this article can be found online at doi:10.1016/j.brainres.2011.07.017.

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