

## FEATURE ARTICLE

# Priming and Backward Influences in the Human Brain: Processing Interactions during the Stroop Interference Effect

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**This study investigated neural processing interactions during Stroop interference by varying the temporal separation of relevant and irrelevant features of congruent, neutral, and incongruent colored-bar/color-word stimulus components. High-density event-related potentials (ERPs) and behavioral performance were measured as participants reported the bar color as quickly as possible, while ignoring the color words. The task-irrelevant color words could appear at 1 of 5 stimulus onset asynchronies (SOAs) relative to the task-relevant bar-color occurrence: –200 or –100 ms before, +100 or +200 ms after, or simultaneously. Incongruent relative to congruent presentations elicited slower reaction times and higher error rates (with neutral in between), and ERP difference waves containing both an early, negative-polarity, central-parietal deflection, and a later, more left-sided, positive-polarity component. These congruency-related differences interacted with SOA, showing the greatest behavioral and electrophysiological effects when irrelevant stimulus information preceded the task-relevant target and reduced effects when the irrelevant information followed the relevant target. We interpret these data as reflecting 2 separate processes: 1) a ‘priming influence’ that enhances the magnitude of conflict-related facilitation and conflict-related interference when a task-relevant target is preceded by an irrelevant distractor; and 2) a reduced ‘backward influence’ of stimulus conflict when the irrelevant distractor information follows the task-relevant target.**

**Keywords:** conflict processing, event-related potentials (ERPs), incongruency, stimulus onset asynchrony (SOA), Stroop task

## Introduction

Models of forced-choice decision making rely heavily on the notion that the brain accumulates information for one stimulus versus others over some period of time, with the resulting choice being determined by the relative weight of this information at a decision stage (Gold and Shadlen 2000; Schall 2001; Platt 2002; Ratcliff et al. 2003; Reddi et al. 2003; Ratcliff and Smith 2004). Computational and neural models of information processing assume that this accumulation is driven by both systematic and random influences that alter the speed and strength of representations in the brain, thereby determining the relative strength of each choice when the response system is activated.

The classic Stroop interference task (Stroop 1935) has provided a fruitful platform by which to test models of forced-choice decision and response selection under situations where compatible or incompatible components of the stimulus facilitate or impair task performance. In the typical Stroop task, participants are instructed to report the physical color of a written color word (e.g., “RED”), while ignoring the semantic

meaning of the word. In cases where the physical color of the presentation is congruent with the semantic meaning of the word, participants are both faster and more accurate at reporting the physical color. However, when the physical color differs from the semantic meaning of the word (i.e., is incongruent) participants are slower and more prone to error (see MacLeod 1991 for a review).

Numerous theoretical accounts of Stroop interference have been proposed over the more than 70-year history of this phenomenon. Although early speed-of-processing (“horse race”) models interpreted Stroop effects as resulting from the faster, more “automatic” processing of word information (Dyer 1973; Posner and Snyder 1975; Dunbar and MacLeod 1984), more recent theoretical and computational explanations of Stroop-related interference have tended to model the effects as arising from response competition occurring in a parallel and hierarchical network (Cohen et al. 1990; Cohen et al. 1992; Phaf et al. 1990; Stafford and Gurney 2007). Under such ‘connectionist’ frameworks, processing is determined by activity spreading throughout pathways of differing strengths, with the response decision ultimately occurring when the output of these pathways crosses a certain threshold (Rumelhart et al. 1986). According to these views, interference occurs when 2 simultaneously activated pathways produce conflicting activity at their processing intersection, whereas facilitation occurs when the 2 paths produce compatible activation. The intersection of conflicting activity can occur at any phase in the processing hierarchy (e.g., semantic evaluation or response selection) following sensory processing, where the pathways rely upon a common set of processing resources, a notion that has been called the “multiple-resource” view (Allport 1982; Hirst and Kalmar 1987; Cohen et al. 1990).

One key piece of evidence that has argued against a simple speed-of-processing account came from behavioral experiments in which the color and word components of the Stroop stimulus were presented with varying stimulus onset asynchronies (SOAs) (Dyer 1971; Glaser and Glaser 1982; Glaser and Dungenhoff 1984; Glaser and Glaser 1989; Sugg and McDonald 1994). In these experiments, the task-relevant stimulus component could be preceded or followed by presentation of the task-irrelevant component with SOAs typically ranging from –400 to +400 ms. If interference in the Stroop task was due to word meaning being processed faster than the physical color, then presenting the color information earlier should give its processing a sufficient head start to eliminate interference from the word-meaning information. Similarly, if the participant’s task was to report the word name, and the physical-color information was presented early enough, it should be possible to elicit a robust “reverse Stroop” effect in

which the processing of the color information would temporally coincide with the processing of the word, therefore creating interference in the naming of the word. Neither of these types of results are typically observed, however (MacLeod 1991; MacLeod and MacDonald 2000). Thus, although pre-exposure to a task-irrelevant color component did not have an effect on naming the word, pre-exposure of the task-irrelevant word did have a substantial effect on naming the physical color. Moreover, such interference was observed even if the word was presented up to 100 ms after the physical color. These SOA manipulations, and resultant data patterns, have called into question the idea that interference arises strictly because words are processed faster than color, suggesting rather that interference is due to interactions that alter the strength of activation patterns in a distributed and parallel network.

### ***Temporal Relationships in the Stroop SOA Task—Priming and Backward Influences***

As illustrated by the Stroop SOA manipulations, successful goal-oriented behavior involves the filtering of task-irrelevant information, especially when it is conflicting or distracting in some way. It is also well appreciated, however, that the temporal relationship between the components of visual stimuli greatly influences the processing and perception of those stimuli.

Priming reflects one such category of stimulus-stimulus temporal interactions in which processing of a target stimulus is altered when it is preceded by a meaningfully related “prime” stimulus. These automatic (or implicit) effects can occur either on the basis of perceptual features of the stimulus, such as color (Marcel 1983) or motion (Jiang et al. 2002), or on the basis of semantic aspects of the stimuli (reviewed in Neely (1991), even in the absence of conscious awareness (Marcel 1983). Although priming is most typically associated with enhanced processing of a stimulus due to the occurrence of a previous stimulus, it has also been shown that there are types of priming that can exert negative, inhibitory influences (Tipper 2001).

In contrast, when a target is followed in time by the subsequent presentation of an irrelevant distractor, backward influences may occur (reviewed in Enns and Di Lollo 2000). Although these influences can also in theory act to facilitate or inhibit target processing, they are most commonly demonstrated as the relative reduction in perceptibility of a target when information is lost because of interference by a subsequently presented stimulus. Such ‘backward masking’ is generally believed to be a precategorical process that depends entirely on the sensory aspects of the 2 inputs and not on lexical or semantic factors. Because Stroop SOA variants, such as the one used in the present study, reflect processing interactions that may be either facilitatory or inhibitory in nature, we refer more generally to instances in which the irrelevant stimulus component is presented prior to the relevant target as “priming influences” and instances when the irrelevant stimulus component comes after the target as “backward influences.”

### ***ERPs as a Measure of Stimulus Conflict and Semantic Processing***

Event-related potentials (ERPs) provide a measure of brain dynamics with high temporal resolution, allowing researchers to characterize the cascade of processes that behavioral measures

such as reaction time cannot offer. ERPs therefore constitute a quantitative measure optimally suited for delineating the nature of cognitive interference effects, such as those elicited by the Stroop task.

Previous applications of Stroop-related ERPs have described 2 principle interference-related response components (Rebai et al. 1997; West and Alain 1999; Liotti et al. 2000; Atkinson et al. 2003; Hesse et al. 2003; West 2003; Markela-Lerenc et al. 2004; West et al. 2005; Hanslmayr et al. 2008). The first is a central-medial component extending from roughly 350- to 500-ms poststimulus that is more negative for incongruent relative to congruent trials. This component has generally been viewed as reflecting the detection and/or resolution of response conflict and is believed to arise, at least partially, from generators in the anterior cingulate cortex (ACC). A second ERP response component, observed between 500 and 900 ms, is more positive for incongruent relative to congruent trials. This late positive complex (LPC) has tended to be maximal over the left parietal cortex and has been related to the processing of semantic meaning of words (West and Alain 1999; Liotti et al. 2000). Taken together, these findings, along with the lack of congruency effects on sensory ERP components (Duncan-Johnson and Kopell 1981; Ilan and Polich 1999; Rosenfeld and Skogsberg 2006) have suggested that Stroop interference does not influence sensory processing, but rather occurs later at stages of response selection (Hanslmayr et al. 2008).

Stroop-like and priming influences share similarities in that both relate to biasing in perceptual systems; therefore, they have sometimes been described in similar cognitive and mechanistic terms (MacLeod 1991; MacLeod and MacDonald 2000). For example, the N400 ERP, a broad negative ERP wave over central-parietal scalp locations, has been shown to be sensitive to semantic priming effects and accordingly has been often used as a marker of semantic processing (Kutas and Hillyard 1980; Kutas and Federmeier 2000). This component is larger for words that are semantically incongruent versus semantically congruent with a preceding priming word or sentence. Because the N400 depends substantially on the temporal separation of the prime and the target (Kiefer and Spitzer 2000; Kiefer and Brendel 2006), it is thought to reflect effects on the processing of the target word resulting from the preactivation of semantic representations of words associated with the prime. Although functional similarities between the semantic N400 component and the Stroop-evoked negativity have been noted, it is thought that the Stroop response reflects interference interactions amongst more general central-executive control processes rather than more specifically semantic incongruency effects (West 2003; West et al. 2004; Hanslmayr et al. 2008). Nonetheless, the observation that the N400 is sensitive to the temporal relationship between stimulus components suggests the utility of similar SOA manipulations on the Stroop interference ERP effect.

### ***Experimental Goals***

The goal of the present study was to investigate the temporal sensitivity of brain processes that detect and resolve stimulus conflict using modified versions of the classic Stroop paradigm. In separate experimental sessions, reaction times and error rates were collected with and without concurrently recorded ERPs as subjects reported the physical color of the stimulus. In these tasks, stimuli were presented with 5 levels of SOA, in which the relative timing of the physical-color and color-word

components of the stimuli were varied from trial-to-trial. This approach of presenting the task-relevant stimulus component first (“relevant-first”) or the task-irrelevant component first (“irrelevant-first”) allowed us to examine the influence of pre- and postexposure of congruent versus incongruent information on both behavior and brain activity.

In our main experimental session we assess the behavioral and neural responses elicited by stimulus incongruency by considering the ERP difference waves produced by subtracting congruent from incongruent trials, and we then relate these “incongruency difference waves” at the different SOAs to behavioral performance on this task. We explicitly focus our ERP analyses here on the incongruency difference waves, because the SOA manipulation utilized in these experiments introduces differential amounts of overlap in the ERP record depending on the temporal separation between stimulus components (Woldorff 1993). As this overlap is equivalent for the congruent and incongruent stimuli within each SOA condition, the difference wave isolates processes related to the Stroop stimulus incongruency and serves as a principled ERP marker for assessing interactions between the SOA and the neural processing related to the conflict processing interactions. In an additional behavioral control study, we evaluate the role of both facilitation and inhibition by comparing reaction times and error rates for compatible and incompatible color-word pairings in relation to a task-neutral control condition.

In theory, these SOA manipulations could have resulted in several outcomes relating to behavioral performance and/or the amplitude or latency of the Stroop ERP effects. For example, based on the common observation that mainly the amplitude, and not the latency, of the language-related N400 component is modulated by the strength of the prime-target semantic relationship (Kutas and Federmeier 2000), our SOA manipulation might only manifest as amplitude changes in the ERP incongruency effects. Alternatively, the pretarget stimulus may serve to alter the temporal characteristics of the processing of the upcoming target, in which case the response latency of the ERP incongruency effects may also be influenced. Nonetheless, in line with the priming and backwards influences discussed above, we would expect that pretarget exposure of the irrelevant stimulus is likely to result in the largest and earliest incongruency effects in relation to simultaneous presentation, and that the effects of post-target exposure to the irrelevant stimulus is likely to be relatively diminished and delayed.

## Methods

### Participants

Forty young adults with normal or corrected-to-normal visual acuity participated in these experiments. Twenty-five participants (19–37 years, 12 females) served as subjects in the “Main Experiment” and 15 participants (18–35 years, 7 females) served as subjects in the additional ‘Behavioral Control’ task carried out in separate sessions. Four participants participated in both experimental sessions. All participants were screened for colorblindness, and informed consent was obtained prior to experimentation under a protocol approved by the Duke University Institutional Review Board. Participants were instructed on the task and given practice experimental runs prior to the start of the experiment. All participants were paid \$10/h for their participation.

### Experimental Designs

Separate experimental sessions were conducted in which subjects performed modified versions of the classic Stroop paradigm (see

Supplementary Materials for stimulus movies). In the main experimental session, reaction times and error rates were monitored as whole-head 64-channel electroencephalography (EEG) was recorded. In the separate, additional, behavioral control session, reaction times and error rates were monitored as participants viewed an extended set of stimulus conditions that included a neutral distractor condition, but with no EEG recorded.

In both experimental variants of the task, the physical “bar-color” and semantic “color-word” components of the stimulus were presented with 5 levels of temporal asynchrony. As depicted in Figure 1, the bar color (always presented at time 0) could co-occur with a simultaneously presented color-word (no-delay), or be either preceded or followed by the presentation of the color-word, by either 100 or 200 ms. In all cases the participants’ task was to report the color of the bar as quickly as possible by pressing 1 of 4 keys on the keyboard corresponding to the 4 possible colors, while ignoring the task-irrelevant color-word. We reference each SOA condition to the no-delay (0 ms) condition, and therefore refer to those trials in which the color-word component came first as the “irrelevant-first” (–200 irrelevant-first and –100 irrelevant-first) conditions, and those trials in which the colored bar appeared first as the “relevant-first” (+100 relevant-first and +200 relevant-first) conditions. For short hand, these SOA conditions may be referred to by their relative timing; –200, –100, 0, +100, +200, or more generally as being negative and positive SOAs.

In the main experimental session, the colored bars were red, green, blue, or yellow rectangular patches, whereas the color words were the text strings “RED,” “GREEN,” “BLUE,” or “YELLOW,” written in white font with black borders. Red and green responses were mapped to the “D” and “F” keys on the left hand, and blue and yellow were mapped to the “J” and “K” keys on the right hand. Stimuli were presented on a gray screen (luminance value: 40 cd/m<sup>2</sup>) with a white fixation cross at the center. Colored bars subtended 5° × 16° of visual angle and were presented 3.75° below fixation. Participants were positioned 60 cm away from the computer screen.

In this task variant, only congruent and incongruent trials were presented and these occurred in equal numbers for all the SOA delays (Fig. 1B). On half the trials, the color-bar and color-word combinations matched (congruent, e.g., red–red), whereas the other half of the trials were split evenly between the 3 possible noncorresponding mappings (incongruent, e.g., red–yellow, red–green, and red–blue). On every trial, the bar and the word remained on the screen together for 1000 ms after the onset of the later stimulus component. Each run consisted of 48 trials randomized across conditions and word/color combinations, with equal numbers of trials occurring for each SOA condition. A run lasted approximately 3 min.

The behavioral control variant of this task was identical in form to the main experiment described above, with the addition of 3 types of neutral stimulus trials. On these trials “PINK,” “ORANGE,” or “BROWN” text strings could appear at any of the SOA conditions. In that pink, orange, and brown were not mapped to any of the target responses, they therefore served as neutral, task-irrelevant controls. Congruent, neutral, and incongruent trials were presented in equal numbers (33% each), and subjects were again instructed to respond as quickly possible by pressing 1 of 4 keys on the keyboard corresponding to the 4 possible bar colors, while ignoring the task-irrelevant color words.

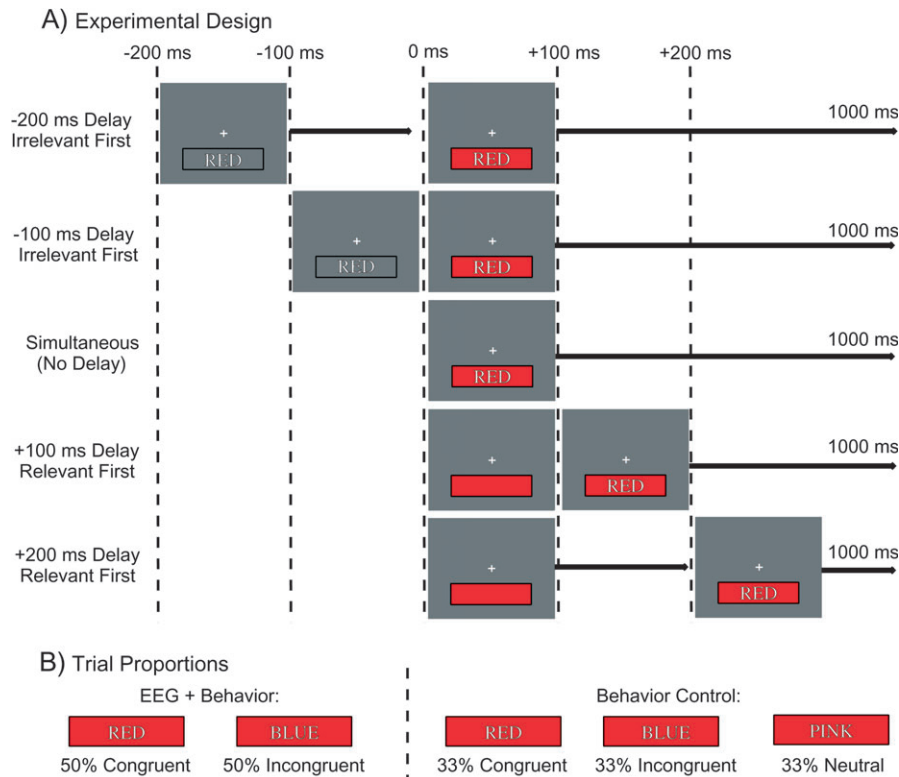
For both tasks, participants were instructed to maintain central fixation and encouraged to minimize eye blinks during the experimental run. Before recording began, participants were given 1 or 2 training runs, each consisting of 48 trials, in order to facilitate their learning of the mapping of the 4 color response buttons. Data from twenty runs were collected for each participant in the main experiment, and from 24 runs in the behavioral control session. Participants were given the opportunity to rest between runs.

### Data Acquisition and Analysis

#### Behavioral Analysis

Behavioral responses were monitored and recorded as participants performed the color-discrimination task and were later analyzed for significant differences. Trials were counted as correct if the subject’s response occurred 100–1000 ms following the bar presentation and





**Figure 1.** (A) Schematic illustration of the experimental design for a congruent (red–red) Stroop stimulus presented at each of the 5 SOAs. Each temporal separation (–200, –100, 0, +100, and +200 ms) is shown in a separate row with vertical dotted lines indicating times at which stimuli components were presented. Once both stimulus components were presented, they remained on the screen for an additional 1000 ms for all SOA conditions. The participant’s task was always to report the color of the bar, which is defined as 0 ms in this schematic. (B) Trials proportions and exemplar stimuli for the main experiment and behavioral control variants of the task. See the Supplementary Materials for movies of the stimuli used in the 2 tasks.

corresponded correctly to the physical bar color. In that no systematic differences were observed for responses to the different target colors, data were collapsed over the corresponding color-bar/word combinations to arrive at within-participant mean response times (RTs) and error rates for all condition categories: congruent, neutral, and incongruent instances of the 5 SOA conditions (no-delay, –100 ms irrelevant-first, –200 ms irrelevant-first, +100 ms relevant-first, and +200 ms relevant-first). RTs (excluding erroneous responses) and error rate means for these categories were then computed along with the standard error. *t*-tests were performed on the congruent versus incongruent RTs and error rates, separately at each SOA, to establish the presence of significant behavioral congruency effects. SOA by congruency, 2-way analysis of variance (ANOVA) were performed on the RTs and error rates to determine significant main effects and interactions of experimental conditions on behavioral performance for the main experiment (5 × 2) and behavioral control (5 × 3) sessions. Post hoc single factor ANOVAs were also performed over SOA for the individual condition types in each session. In addition, separate 3 by 2 ANOVAs were performed on the irrelevant-first (–200, –100, and 0) and relevant-first (0, +100, and +200) conditions, to establish the presence of independent pre-exposure and postexposure congruency effects on behavioral performance collected during the EEG sessions. The significance threshold for the behavioral analyses was set to a *P* value of 0.05 and reported using the Greenhouse-Geisser correction for sphericity. The Bonferroni correction was also applied to post hoc pairwise comparisons.

#### EEG Recording and Analysis

The EEG was recorded continuously from 64 channels mounted in a customized elastic cap (Electro-Cap International, <https://www.electro-cap.com>) using a bandpass filter of 0.01–100 Hz, gain of 1000, and sampling rate of 500 Hz (SynAmps, Neuroscan, Charlotte, NC). All channels were referenced to the right mastoid during recording. The

positions of all 64 channels were equally spaced across the customized cap and covered the whole head from slightly above the eyebrows to below theinion posteriorly (Woldorff et al. 2002). Impedances of all channels were maintained to be below 5 k $\Omega$ , and fixation and eye movements were monitored with both electro-oculogram recordings and a zoom-lens camera. Recordings took place in an electrically shielded, sound-attenuated, dimly lit, experimental chamber.

For each participant, ERPs to the onset of the bar color were selectively averaged for each condition and SOA. ERP processing included the re-referencing of all channels to the algebraic mean of the 2 mastoid electrodes and application of a digital, noncausal, 9-point running-average filter. This filter greatly reduces frequencies of 56 Hz and above at our sampling frequency of 500 Hz. Artifact rejection was performed off-line before averaging by using a computer algorithm that discarded epochs of the EEG that exceeded a prespecified threshold in the window from –200 to 900 ms around the presentation of a bar-color stimulus. The artifact rejection thresholds were set individually for each subject, resulting in an average of ~15% of trials being rejected. Five experimental participants were excluded from the analysis due to either electrical noise problems (*N* = 2) or high trial-rejection rates caused by eye blinks (*N* = 3).

Separate ERPs were computed for correctly reported congruent and incongruent presentations for each of the 5 SOA conditions (–200, –100, 0, +100, +200) by time-locking to the onset of the bar stimulus. Because no differences were observed in the ERP responses for the different target colors, responses were collapsed over all corresponding color-bar/word combinations to arrive at 10 (5 SOAs × 2 congruency) evoked response types. To isolate brain potentials related to the Stroop interference effect, difference waves were computed separately for each SOA by subtracting the ERPs for congruent trials from the ERPs for incongruent trials. Because we were interested primarily in the relatively slow activity associated with the cognitive resolution of Stroop interference, we applied an additional 51-point running-average

filter to attenuate high-frequency activity occurring at, or above, 10 Hz. Spherical-spline-interpolated topographic voltage maps of the 20 subject grand-averaged ERP differences were derived for a series of consecutive 50-ms windows spanning from 100- to 900-ms post-color-bar to visualize how the scalp distribution changed over time.

To test for significant differences between the congruent and incongruent waveforms *within SOA conditions*, 2-way repeated-measures ANOVAs were performed using a set of left- and right-sided regions of interest, each consisting of 2 posterior-parietal channels roughly corresponding to the peak of the incongruity-effect distribution (these channels are indicated in orange in the bottom panel of Fig. 3). For each SOA condition, 2-way ANOVAs with factors Trial Type (congruent vs. incongruent) and Laterality (left vs. right) were computed in successive 20-ms windows, with 10-ms overlap, spanning from the onset of the second stimulus component to 900 ms after the onset of the relevant target. Each time window was compared with the prestimulus baseline, defined as the 200 ms preceding the presentation of the initial stimulus component for each SOA. Latency ranges with greater than 3 consecutive windows exceeding the  $P < 0.05$  level were determined to be significant, and 2-way interactions between hemisphere and trial type were only considered over those latency ranges that showed a main effect of trial type.

In order to statistically assess the pattern of ERP latency and amplitude effects *between SOA conditions*, we submitted the individual subjects' peak-latency and peak-amplitude values to repeated-measures ANOVAs. For each participant, and at each SOA, the peak-latency and peak-amplitude within the significant latency ranges defined by the within-SOA analyses were extracted from the incongruity difference waves and averaged across the 4 channels of interest. The means of these individual subject peak-latency and peak-amplitude measures were then submitted to a within-subject, 1-factor ANOVA with SOA (-200, -100, 0, 100, 200) as the single factor.

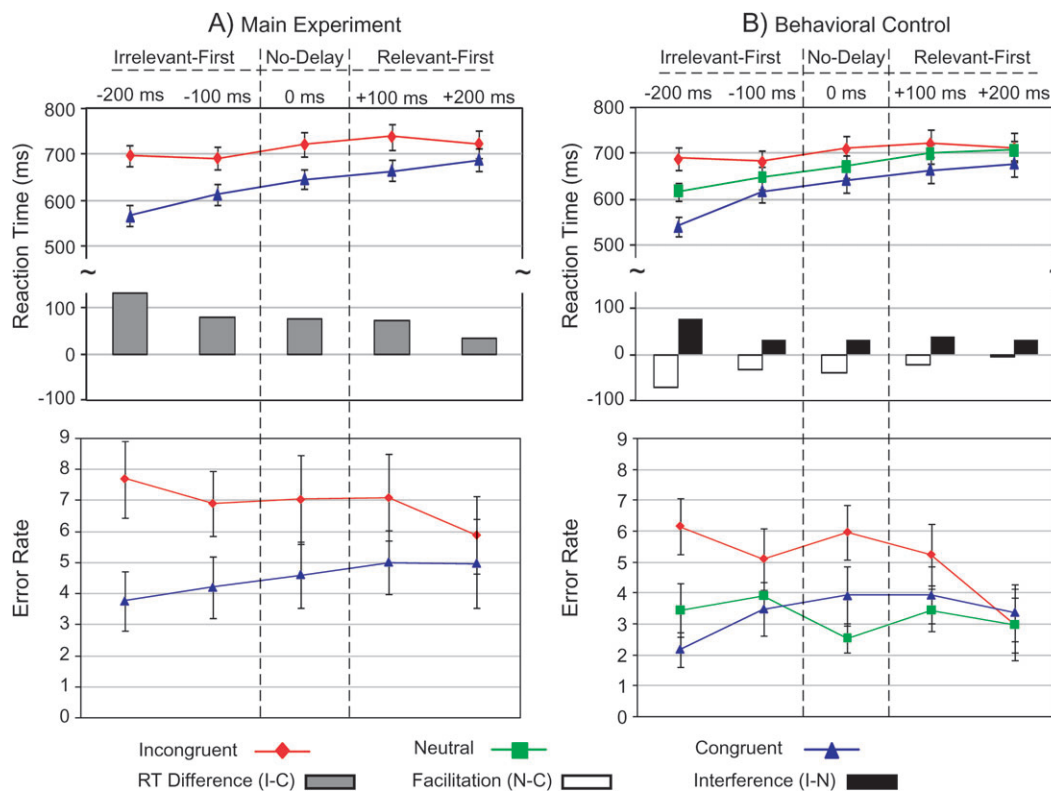
## Results

### Behavioral Performance

Robust and statistically significant behavioral effects of stimulus compatibility were observed in both the main experiment and in the behavioral control variants of these tasks. For both task variants, RTs were faster and error rates lower for congruent trials than for incongruent trials. Mean reaction times and error rates for the 2 sessions are shown graphically in Figure 2 and presented along with paired *t*-test results in Table 1.

### Main Experiment

Analysis of the behavioral data collected during the main experimental session indicated that RTs for congruent trials were faster than for incongruent trials for each of the SOA conditions. Error rates for congruent trials were also lower than for incongruent trials for all SOAs, with the exception of the +200 SOA conditions, which did not reach significance at the  $P < 0.05$  level. For general statistical evaluation of these data,  $2 \times 5$  (congruency by SOA) repeated-measures ANOVAs were performed separately on the RT and percent-error data. The ANOVA for reaction times demonstrated a significant main effect of congruency ( $F_{1,19} = 204.9, P < 0.001$ ) and of SOA ( $F_{4,76} = 46.2, P < 0.001$ ), and a significant congruency by SOA interaction ( $F_{4,76} = 16.8, P < 0.001$ ). For the error rates, the 2-way ANOVA showed only a significant main effect of congruency ( $F_{1,19} = 16.0, P = 0.001$ ). To further probe the driving influences in the congruency by SOA interaction, 1-way



**Figure 2.** Behavioral performance for data collected during the main experiment (A) and the behavioral control experiment (B) are shown as a function of SOA. Data in the top panels show reaction times for Incongruent (red), Neutral (green), and Congruent (blue) trials. Congruency differences are shown as gray bars for the Incongruent minus Congruent reaction times in the main experiment, and separated into RT Facilitation (white: Congruent minus Neutral) and Interference (black: Incongruent minus Neutral) in the behavioral control experiment. Mean error rates are shown in the bottom panels for each condition using the same color convention as in above.

**Table 1**

Summary of behavioral performance data

SOA	RT difference	<i>t</i>	Significance	Error rate	<i>t</i>	Significance
Main experiment (incongruent minus congruent):						
-200	131.80	<i>t</i> (19) = -12.47	<i>P</i> < 0.001	3.93	<i>t</i> (19) = 3.33	<i>P</i> = 0.001
-100	79.23	<i>t</i> (19) = -10.83	<i>P</i> < 0.001	2.70	<i>t</i> (19) = 2.62	<i>P</i> = 0.008
0	75.23	<i>t</i> (19) = -7.82	<i>P</i> < 0.001	2.42	<i>t</i> (19) = 1.95	<i>P</i> = 0.035
100	74.28	<i>t</i> (19) = -10.25	<i>P</i> < 0.001	2.09	<i>t</i> (19) = 2.23	<i>P</i> = 0.017
200	35.41	<i>t</i> (19) = -3.17	<i>P</i> = 0.002	0.92	<i>t</i> (19) = 0.9	<i>P</i> = 0.19
Behavioral control (incongruent minus neutral):						
-200	75.61	<i>t</i> (14) = -7.37	<i>P</i> < 0.001	1.27	<i>t</i> (14) = -4.04	<i>P</i> = 0.001
-100	30.27	<i>t</i> (14) = -4.55	<i>P</i> < 0.001	0.44	<i>t</i> (14) = -1.1	<i>P</i> = 0.29
0	29.37	<i>t</i> (14) = -4.44	<i>P</i> < 0.001	-1.37	<i>t</i> (14) = -2.55	<i>P</i> = 0.023
100	36.13	<i>t</i> (14) = -1.86	<i>P</i> = 0.08	-0.48	<i>t</i> (14) = -2.50	<i>P</i> = 0.025
200	29.96	<i>t</i> (14) = -0.7	<i>P</i> = 0.5	-0.39	<i>t</i> (14) = 0.01	<i>P</i> = 0.99
Behavioral control (neutral minus congruent):						
-200	72.00	<i>t</i> (14) = -10.3	<i>P</i> < 0.001	2.71	<i>t</i> (14) = -2.04	<i>P</i> = 0.03
-100	34.68	<i>t</i> (14) = -4.75	<i>P</i> < 0.001	1.19	<i>t</i> (14) = -0.45	<i>P</i> = 0.32
0	39.50	<i>t</i> (14) = -4.1	<i>P</i> < 0.001	3.43	<i>t</i> (14) = 1.90	<i>P</i> = 0.038
100	22.66	<i>t</i> (14) = -3.46	<i>P</i> < 0.003	1.79	<i>t</i> (14) = 0.47	<i>P</i> = 0.32
200	5.85	<i>t</i> (14) = -2.12	<i>P</i> = 0.05	0.00	<i>t</i> (14) = 0.45	<i>P</i> = 0.33
Behavioral control (incongruent minus congruent):						
-200	147.62	<i>t</i> (14) = -15.22	<i>P</i> < 0.001	3.98	<i>t</i> (14) = -4.17	<i>P</i> < 0.001
-100	64.94	<i>t</i> (14) = -5.75	<i>P</i> < 0.001	1.63	<i>t</i> (14) = -1.33	<i>P</i> = 0.20
0	68.87	<i>t</i> (14) = -6.66	<i>P</i> < 0.001	2.06	<i>t</i> (14) = -1.78	<i>P</i> = 0.09
100	58.80	<i>t</i> (14) = -3.85	<i>P</i> < 0.001	1.32	<i>t</i> (14) = -1.35	<i>P</i> = 0.19
200	35.81	<i>t</i> (14) = -2.65	<i>P</i> = 0.01	-0.40	<i>t</i> (14) = 0.59	<i>P</i> = 0.55

Note: Group mean RT (left) and percent error (right) differences and paired *t*-test results for all within-SOA contrasts of congruent, neutral, and incongruent trials.

ANOVAs were performed on the reaction time data separately for the congruent and the incongruent trials. Between-condition comparisons revealed a main effect of SOA for the congruent ( $F_{4,95} = 4.31, P = 0.003$ ), but not incongruent ( $F_{4,95} = 0.530, P = 0.714$ ) trials. Subsequent planned comparisons of the congruent SOA conditions revealed only differences between the -200 SOA and the +100 and +200 SOA conditions.

Two,  $2 \times 3$  ANOVAs done separately on the RTs for pre-exposure (-200, -100, 0) and postexposure (0, 100, 200) SOAs each showed main effects of congruency (pre-exposure: [ $F_{1,19} = 69.5, P < 0.001$ ]; postexposure: [ $F_{1,19} = 285.8, P < 0.001$ ]), SOA (pre-exposure: [ $F_{2,38} = 7.13, P = 0.002$ ]; postexposure: [ $F_{2,38} = 45.3, P < 0.001$ ]) and SOA by congruency interactions (pre-exposure: [ $F_{2,38} = 9.8, P < 0.001$ ]; postexposure: [ $F_{2,38} = 12.3, P < 0.001$ ]) on RT, supporting the view that pre-exposure and postexposure can each separately produce interference effects that vary as a function of the distractor-target relative timing.

### Behavioral Control Experiment

As shown in Figure 2B for responses collected during the behavioral control session, reaction times were fastest for congruent, intermediate for neutral, and slowest for incongruent trials. Statistical evaluation of the reaction times and performance errors was done by way of separate  $3 \times 5$  (congruency by SOA) repeated-measures ANOVAs. As observed in the main experiment, a significant main effects of congruency ( $F_{2,28} = 50.26, P < 0.001$ ), of SOA ( $F_{4,56} = 78.4, P < 0.001$ ), and a congruency by SOA interaction ( $F_{8,112} = 13.15, P < 0.001$ ) were all present. Separate 1-way ANOVAs, performed on the reaction time data, demonstrate a main effect of SOA for the congruent ( $F_{4,70} = 4.69, P = 0.002$ ) and neutral ( $F_{4,70} = 2.56, P = 0.046$ ) trials, but not for the incongruent ( $F_{4,70} = 0.44, P = 0.78$ ) trials. Subsequent planned comparisons of the congruent, neutral, and incongruent trial types revealed significant differences between the -200 SOA and the +100 and +200 SOA

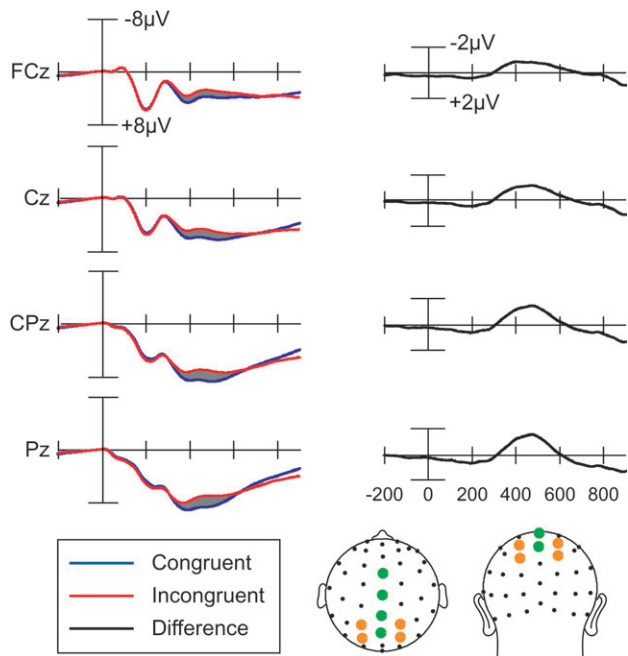
conditions for congruent trials, and between the -200 and +200 SOA conditions for the neutral trials. Repeated-measures ANOVA computed on the performance errors showed a significant main effect of congruency ( $F_{2,28} = 5.98, P = 0.007$ ) and SOA by congruency interaction ( $F_{8,112} = 2.76, P = 0.008$ ), though the main effect of SOA ( $F_{4,56} = 1.59, P = 0.19$ ) did not reach statistical significance. See Table 1 for specific within-SOA contrasts of congruent, neutral, and incongruent RTs and error rates.

As done with the main experiment, separate ANOVAs were also performed on the RTs for pre-exposure (-200, -100, 0) and postexposure (0, 100, 200) SOAs. Each showed main effects of congruency, SOA, and an SOA by congruency interaction, again supporting the view that pre-exposure and postexposure can each separately produce interference effects that vary as a function of the distractor-target relative timing.

Collectively, data from these 2 tasks emphasize the relationship between the temporal separation of the Stroop components and the stimulus congruency. Specifically, we observed that, for both tasks, pre-exposure of a task-irrelevant color-word (negative SOAs) enhances the magnitude of the behavioral incongruency effect on the subsequent target relative to when they were presented simultaneously. Post-target exposure of an irrelevant distractor, on the other hand, reduced the overall magnitude of this effect relative to the no-delay condition, while still producing statistically significant interference. Importantly, data from the behavioral control task demonstrate a main effect of SOA on the RTs of the neutral trials, strongly suggesting that pre-exposure of the distractor stimulus influences performance irrespective of its compatibility with the upcoming target.

### ERPs for the No-Delay Condition

Grand average (left) and difference wave (right) ERPs for the no-delay condition are shown in Figure 3 for 4 mid-line channels, FCz, Cz, CPz, and Pz. As observed in previous studies

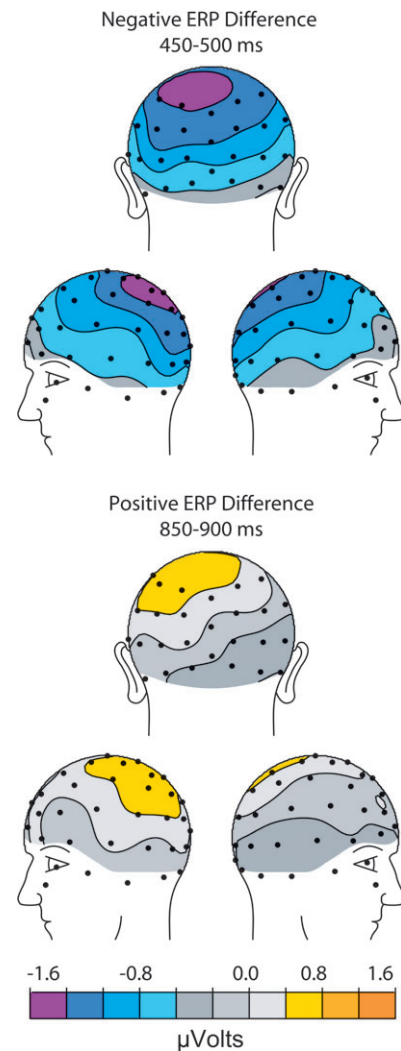


**Figure 3.** Grand average ERPs (left) and incongruent minus congruent difference waves (right) are shown for the no-delay condition of the Stroop color-discrimination task. ERPs are shown for congruent (blue) and incongruent (red) trials at 4 midline channels (FCz, Cz, CPz, and Pz). The location of these channels are indicated in green in the key at the bottom. Channels marked in orange around the peak of the effect were subjected to repeated-measures ANOVAs.

(Hanslmayr et al. 2008; Liotti et al. 2000; West 2003; West and Alain 1999), ERP waveforms for congruent (blue) and incongruent (red) color-word pairs diverge between 300 and 500 ms. This congruency effect is globally reflected as increased negative-polarity electrical brain activity over central-parietal regions for the incongruent trials as compared with the congruent trials. In addition, a second, later difference is observed in the latency window between 550 and 900 ms in which incongruent trials elicit a more positive deflection over parieto-occipital sites as compared with congruent trials. The spatiotemporal distribution of this effect closely resembles that of the LPC reported by other investigators (West and Alain 1999; Liotti et al. 2000), and we have adopted this nomenclature here. The spatial distribution of the negative (top) and positive (bottom) components for the no-delay condition can be seen in Figure 4. These maps are averaged over the 50-ms interval spanning the peak of the amplitude differences and are shown as spline-interpolated flat maps on posterior and lateral views of the head.

### ***Congruency Effects as a Function of SOA***

Varying the SOA of the presentation of the colored-bar and color-word components of the stimulus modulates the timing of the arrival of conflicting versus congruent information to the brain areas that detect and resolve conflict. The difference between the brain responses to congruent and incongruent stimuli is believed to index this conflict-related activity and therefore provides a principled marker by which to compare the influence of SOA on the neural processes underlying Stroop-related conflict resolution. Here we begin by separately considering difference-wave activity for the irrelevant-first and relevant-first SOA conditions.



**Figure 4.** Spatial distribution of the negative-polarity (top) and later positive-polarity (bottom) incongruency ERP effects for the no-delay SOA condition. Note that these differences maps are also indicated with asterisks “\*” in Figure 6.

Incongruency difference waves, computed as the incongruent minus congruent ERPs, are shown on separate plots for the irrelevant-first (left) and relevant-first (right) SOA conditions over 4 midline channels in Figure 5. The difference waves for the no-delay condition (also seen in the right panel of Fig. 3) are shown in both of these plots (black traces). We present the irrelevant and relevant-first waveforms on separate plots here both for clarity of presentation and to illustrate the differential influence of pre- and post-target distractor presentations on the Stroop incongruency difference potential.

### ***Irrelevant-First Difference Waves***

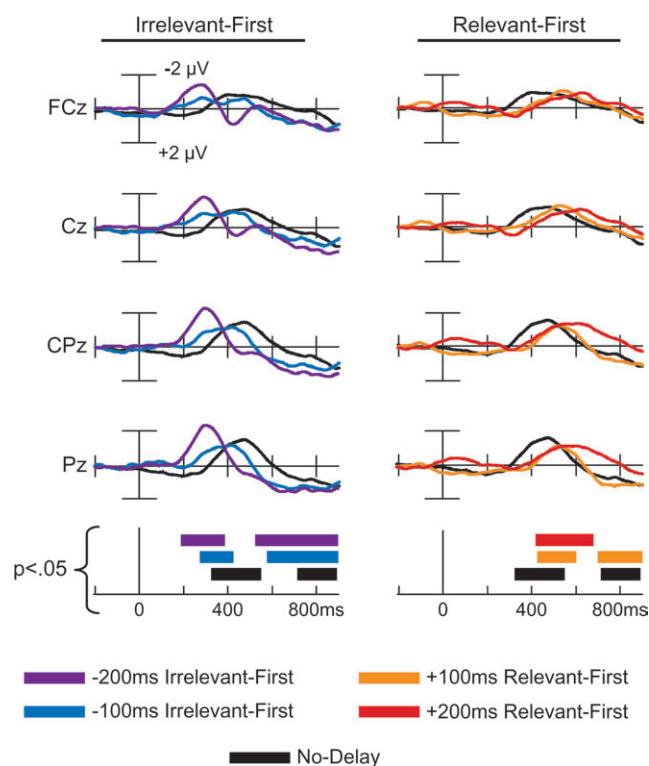
For the irrelevant-first conditions, the difference waves show a prominent negative deflection followed by a positive deflection at all SOAs. This pattern is globally similar to previous reports of simultaneous-presentation Stroop tasks (Rebai et al. 1997; West and Alain 1999; Liotti et al. 2000; Atkinson et al. 2003; West 2003; Hesse et al. 2003; Markela-Lerenc et al. 2004; West R et al. 2005; Hanslmayr et al. 2008), but the current data now include a manipulation of the relative timing of the



irrelevant and relevant stimulus components. The largest and earliest incongruent-versus-congruent negative-wave deflections were observed for the -200 ms irrelevant-first condition (Fig. 5, purple), consistent with the pattern of reaction time differences present in the behavioral data (see Fig. 2 and Table 1).

Difference-wave activity shows a significant monotonic shift in onset and offset latency for the negative deflection across the irrelevant-first conditions, as indicated by within-SOA-condition ANOVA test results (see Methods). Those time points that reached statistical significance at the  $P < 0.05$  level are shown by the colored bars presented below the difference waves in Figure 4 and are included in Table 2.

In addition to the negative-polarity congruency ERP effects, statistically significant time points are also present at later latencies for the positive-polarity deflection. This positive deflection shows a similar monotonic shift with SOA as seen in the earlier negative deflection and resembles the LPC observed in other Stroop ERP task variants (West and Alain 1999; Liotti et al. 2000). Trial-by-hemisphere interactions are present in the LPC response for the -200 and -100 irrelevant-first conditions. The spatial distribution of these effects can be seen in Figure 6 (rows 1 and 2) as having a left-sided parietal distribution.



**Figure 5.** Group average difference waves (incongruent minus congruent) are shown separately for irrelevant-first (left) and relevant-first (right) conditions, with the no-delay difference wave (black traces) present in both sets of plots. Irrelevant-first difference waves shifted monotonically as a function of SOA, with the -200 ms condition showing the largest and temporally sharpest amplitude difference (purple traces). Relevant-first difference waves did not show a strictly monotonic shift, with the +100 and +200 SOA difference waves initiating at nearly the same increased latency relative to the no-delay condition effect, but with the +200 condition effect offsetting later. Horizontal bars below the difference waves correspond to the time points that showed a main effect of congruency according to ANOVAs performed on the 4 channels surrounding Pz (highlighted in orange in Figure 3 inset). These bars are color coded with the same condition convention as for the difference waves.

### Relevant-First Difference Waves

Difference waves as computed here index the neural activity relating to the incongruity versus the congruency of the task-relevant and task-irrelevant stimulus components. Because the word element would theoretically be able to cause interference if it appears at any point before the completion of the color processing, positive-SOA ERP differences should reflect the influence of postexposure of the irrelevant stimulus feature on the processing of the relevant target, an effect we are referring to here as “backward influence.”

Relevant-first difference waves and ANOVA test results are shown on the right side of Figure 5. Analogous to the latency shifts seen in the irrelevant-first conditions, the +100 SOA relevant-first ERP difference wave (orange) shows a similar 100-ms latency shift when compared with the no-delay condition (black). Delaying the irrelevant input an additional 100 ms (to +200 ms), however, had relatively little influence on the onset latency of the congruency difference wave. This can be seen both in the overlapping onset of the difference response for the +100 (orange) and +200 (red) SOA conditions, and in the ANOVA test results depicted graphically at the bottom of Figure 5 and entered into Table 2. Interestingly, the offset of this negative deflection for the +200 SOA condition does show a consistent, monotonic shift relative to the +100 SOA, suggesting that the duration of the processes generating the difference wave is not fixed, but rather depends on the temporal arrangement of the inputs. Lastly, a late positive difference is present for both the no-delay and +100-ms SOAs that initiates at roughly the same latency for these 2 conditions. However, no LPC is seen for the +200 ms SOA, the condition that also shows the smallest behavioral effects.

### Spatiotemporal Distribution of Stroop Incongruity as a Function of SOA

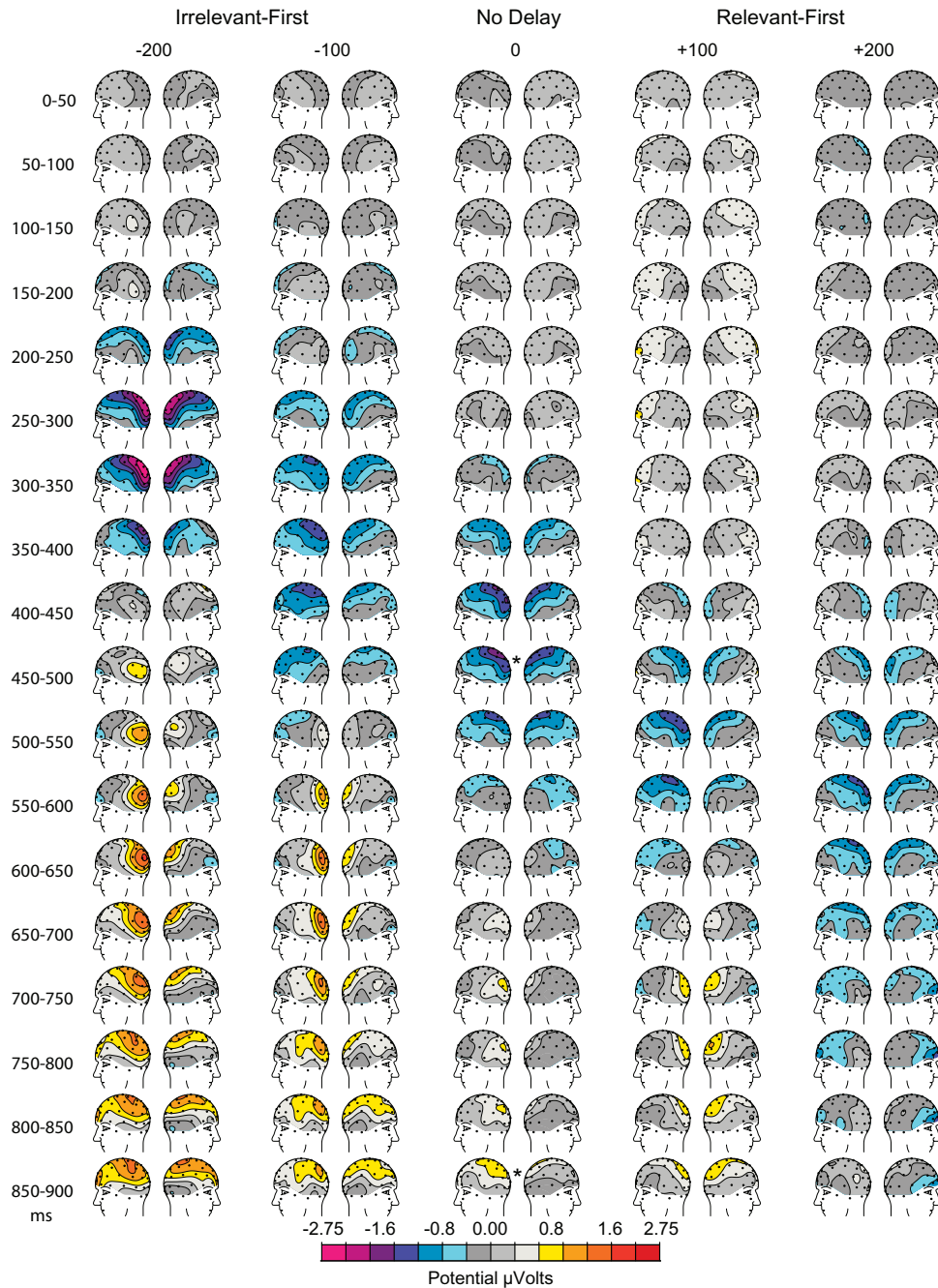
To portray the temporal evolution of the Stroop effects more intuitively for the different SOA conditions, it is useful to visualize the full extent of the ERP difference distribution as it evolves in time for each of these conditions. This spatiotemporal distribution of Stroop interference is shown in Figure 6 as left and right views of the 2-D spline-interpolated topographic maps of the difference-wave activity. These maps are computed as the average activity in 50-ms windows from 0 to 900 ms following the onset of the task-relevant color-bar stimulus. This figure is arranged with each SOA condition presented on

**Table 2**  
Summary of ANOVA results

SOA condition	ANOVA effect	Negativity	Positivity
-200	Trial type	190-390	530-900
	Trial × Hemi		580-790
-100	Trial type	280-430	560-900
	Trial × Hemi		640-780
0	Trial type	330-550	710-890
	Trial × Hemi	400-450	
+100	Trial type	430-600	700-900
	Trial × Hemi		
+200	Trial type	420-690	
	Trial × Hemi		

Note: Significant latency ranges for trial type (congruent vs. incongruent) and trial type by hemisphere interactions are indicated for each SOA condition. Both earlier negative and later positive differences show a monotonic shift with SOA, with the exception of the +200 (relevant-first) condition. Main effects of trial type are shown visually in Figure 4.





**Figure 6.** Spatiotemporal distributions of the congruency-related difference potentials as a function of SOA. The temporal shift due to SOA is evident in these distributions for both the earlier negative-polarity effect (blue/purple) and the later positive-polarity effect (yellow/orange). As seen in the difference waves in Figure 5, these maps also show that the negative-polarity waves for the +100 and +200 ms SOA conditions onset at roughly the same latency.

a separate column with the map latency indicated to the left and the voltage color scale shown below. Time points corresponding to the maps portrayed in Figure 4 are indicated with an asterisk (“\*”).

Figure 6 clearly shows the temporal shift in the incongruency effect resulting from the SOA timing manipulation. Here, a central-parietal negative deflection is present (blue and purple scale colors) that shifts in a largely monotonic and linear manner with stimulus SOA, with the exception of the +200 relevant-first condition (compare with ANOVA test results in Fig. 5 and Table 2). A later, parietal positivity is also present (orange and yellow)

that reaches significance in all but the +200 ms relevant-first condition. Consistent with the trial type by hemisphere ANOVA results (Table 2) some hemispheric laterality is present in the spatial distribution of these effects. In particular, the LPC appears to be more left-side dominant.

***SOA Influences on Peak-Amplitude and -Latency as a Function of SOA***

Results from the within-condition ANOVA tests, and from the visual display of the difference distributions presented in Figure 6,

present a striking qualitative depiction that neural interactions resulting from stimulus incongruency shift monotonically with SOA. This observation is substantiated quantitatively by repeated-measures ANOVAs performed on the ERP difference-wave peak-latency values between the SOA conditions (see Methods). This between-condition ANOVA demonstrates a clear main effect of SOA on the peak-latency of the negative-going ERP deflection ( $F_{4,95} = 103.5, P < 0.001$ ). Subsequent post hoc comparisons revealed significant differences between all the individual SOA conditions except for between +100 and +200 ( $P = 0.13$ ).

Lastly, as noted above, the largest incongruency difference-wave deflections and reaction-time differences were observed for the -200 ms irrelevant-first condition (see Figs 2 and 5). Repeated-measures ANOVAs performed on the ERP peak-amplitudes confirmed a main effect of SOA on the difference-wave amplitudes ( $F_{4,95} = 2.85, P = 0.028$ ), with post hoc comparisons revealing significant differences between the +200 SOA condition and all other conditions ( $P < 0.05$ ). Comparable peak-latency and peak-amplitude analyses were not done on the LPC as not all SOAs had a significant LPC component.

## Discussion

Stroop interference is a widely used marker of cognitive function that has been successfully employed to study the psychological and neural processes of executive attention. In the present study, Stroop incongruency effects were observed in both behavioral and electrophysiological measures across a range of temporal offsets introduced between the physical color and color-word stimulus components. In addition to replicating the well-established behavioral and ERP patterns reported when Stroop stimulus components are presented simultaneously, we observed substantial interactions of SOA with both the reaction times and the ERP congruency-related difference waves. These interactions were manifest as both amplitudes and latency changes with differential effects due to pre-target and post-target SOAs. Our results demonstrated the greatest incongruency effects when an irrelevant stimulus preceded a relevant target (e.g., -200 ms SOA) and reduced effects when an irrelevant stimulus followed a relevant target (e.g., +200 ms SOA).

We interpret this pattern of results as reflecting 2 distinct processes. When the target color-bar is preceded by an irrelevant word stimulus, the increased RT differences and ERP difference-wave amplitudes can be viewed as reflecting a priming mechanism. More specifically, in line with classic theories of perceptual priming (Posner and Snyder 1975; MacLeod 1991), the earlier presentation of an irrelevant word stimulus gives the brain a “head start” in its processing, including that of its semantic characteristics. This head start therefore primes the response selection and results in a greater competitive advantage for when the bar colors match the word meaning, and an increase in interference when they do not match. The present findings further indicate that presenting the irrelevant stimulus prior to the target also appears to serve a general cueing or alerting function, resulting in enhanced processing for all target types that follow, regardless of their congruency relationship to the priming stimulus.

When the to-be-reported, color-bar stimulus is followed by an irrelevant color-word stimulus, a reduction in the Stroop incongruency effect is observed for both RTs and ERP differences, reflecting a diminishing influence of the distractor.

This backward influence can be explained by considering classic models of forced-choice decision making (Ratcliff 1978; Logan 1980; Luce 1986; Rumelhart et al. 1986; Cohen et al. 1990; Cohen et al. 1992; Ratcliff and Smith 2004; Voss et al. 2004) in which evidence accumulates over time until a response threshold is reached (although see Stafford and Gurney 2004, 2007 for discussion of other computational models of Stroop effects). When the color-bar component is presented first (positive SOAs), processing of this task-relevant stimulus proceeds unimpeded for some period of time, allowing more evidence to accumulate in favor of the appropriate response prior to the introduction of the irrelevant stimulus. Under these circumstances, the irrelevant stimulus is in a position of having to catch up and therefore elicits smaller behavioral effects and smaller and later neural effects when presented after a temporal delay.

## SOA and ERP Incongruency Effects

The ERP is a measure of the brain's electrical activity elicited by specific sensory stimuli and cognitive processes. Voltage deflections in the ERP that occur within the first ~200 ms show a characteristic pattern that varies with the sensory characteristics of the evoking stimulus. Deflections occurring later, however, vary more with the cognitive characteristics of processing brought about by the task. ERP components, such as the incongruency difference effect elicited in these tasks, are defined by their relative onset latency, voltage amplitude, scalp distribution, and sensitivity to experimental manipulation, and thus provide a useful measure of the cognitive processes engaged.

In the present experimental design, the SOAs of the task-relevant target and task-irrelevant distractor stimulus components were varied in 100-ms increments, thereby altering the temporal dynamics of the sensory processing of the component parts of the stimuli, as well as the intersection of the processing of the congruent and incongruent components in the brain. By presenting these stimuli at relatively short SOAs, the ERPs to successive stimuli overlap in time with differing amounts of distortion depending on the length of the temporal separation. Although effective methods exist for deconvolving such differential overlap in the ERP waveforms with certain manipulations or control conditions (Woldorff 1993), a particularly pragmatic approach in the current design is to restrict direct comparisons between SOAs to the incongruency (incongruent minus congruent) difference wave. As noted in the introduction, an equivalent amount of overlap is present for the incongruent and congruent trials within a given SOA, and therefore evaluating the difference wave is an effective means to isolate how processes related to the cognitive resolution of stimulus incongruency are influenced by the temporal separation of the stimulus components.

The influence of this temporal manipulation could in principle take many forms in the ERP responses as determined by interactions between the stimulus processing, response selection, and the temporal arrangement of the inputs. As alluded to above (see Introduction), pre-exposure and post-exposure of task-irrelevant information could have affected either the amplitude or latency of the ERP incongruency difference wave, or both. We observed that the SOA manipulation resulted in different modulations to the ERP effect for negative and positive SOAs. First, nearly twice as many

significant time points (as computed by the ANOVA) were present in the negative versus positive SOAs, presumably reflecting the greater neural activity elicited by incompatible information when it arrives earlier to induce perceptual priming. Beyond this, negative-SOA conditions elicited amplitude changes and linear shifts in response latency that corresponded closely to the 100-ms temporal offsets introduced between the stimulus components. Positive SOAs, however, produced amplitude changes and latency shifts that did not shift linearly with the temporal separation introduced between the stimulus components. Specifically, the +200 SOA ERP effect did not adhere to the monotonic shift in response latency nor did it contain a LPC, although it did demonstrate a longer lasting negativity. In addition, this stimulus SOA corresponded to only marginal behavioral effects. Although the functional significance of these observations for the +200 SOA condition is not clear, one possible interpretation is that conflict influence in this case did not ramify into an LPC response due to its late arrival. The interaction with semantic processes—a reported functional correlate of the LPC component (West and Alain 1999; Liotti et al. 2000)—may therefore not have been activated, resulting in relatively weak behavioral incongruency effects.

#### ***Spatiotemporal Distribution of Stroop Incongruency Effects***

Since the earliest application of ERPs in studying the Stroop effect (Scott et al. 1967), dozens of researchers have utilized this technique. Although several groups have reported some small differences in the early sensory components (e.g., Ilan and Polich 1999; Hanslmayr et al. 2008) most have focused on the later cognitive processes related to the incongruency versus congruency of the stimulus components. Though far from exclusive, the majority of ERP results have claimed that the left hemisphere generally shows more electrophysiological interference effects than the right, an observation that appears to also be present in the current results.

Stroop-related incongruency, and stimulus incompatibility more generally, has been associated with function in the ACC, dorsal lateral prefrontal cortex, and the parietal lobe (see reviews by Roberts and Hall 2008; Mansouri et al. 2009). Numerous ERP (Rebai et al. 1997; West and Alain 1999; Liotti et al. 2000; Atkinson et al. 2003; Hesse et al. 2003; West 2003; Markela-Lerenc et al. 2004; West et al. 2005; Hanslmayr et al. 2008) and functional magnetic resonance imaging (fMRI) (Botvinick et al. 1999; Peterson et al. 1999; MacDonald et al. 2000; Botvinick et al. 2004; Kerns et al. 2004; Egner and Hirsch 2005; Polk et al. 2008) studies have indicated that these areas are actively involved in the monitoring for, and adjustment in control due to, stimulus conflict. However, as addressed in a recent review by Mansouri et al. (2009), the relative involvement of these areas in distinct functional operations is still not known.

Although the negative ERP Stroop difference component has typically been modeled as arising from generators in the ACC (Liotti et al. 2000; Hanslmayr et al. 2008), the particular distribution and waveform morphology elicited by the incongruency subtraction has varied considerably with the specifics of the experimental manipulation and response mode. For example, Liotti et al. (2000) observed substantial differences in scalp distributions for verbal-response versus manual-response variants of the task, with a more anterior-medial focus for

verbal responses (both overt and covert) and a broader more centro-parietal distribution for manual ones. Although some other researchers have also reported relatively posterior distributions for Stroop incongruency effects with manual responses (Rebai et al. 1997; West and Alain 1999; Liotti et al. 2000), some others have reported fairly anterior distributions with manual responses (e.g., Markela-Lerenc et al. 2004; Hanslmayr et al. 2008). Regardless, this leaves open the possibility that different sets of neural generators are involved in the selection of competing responses when different output effectors are employed. Beyond this, lesion data have indicated that different portions of the ACC are involved in manual versus verbal responses in the Stroop task (Swick and Turken 2002).

In the present study, the response distribution of the incongruency negativity (see Figs 4 and 6), for all the SOAs, is more posterior and slightly left-sided, consistent with that reported by Liotti et al. (2000) and West and Alain (1999) for a manual-response Stroop task, and potentially consistent with a source in the more posterior regions of the ACC (Liotti et al. 2000). Considering the posterior distribution of this effect, however, another possible explanation is that it derives from a set of parietal generators that are relatively left dominant, perhaps along with contribution from more posterior or medial regions of the cingulate. This interpretation is consistent with numerous reports from neurophysiology (Goodale and Milner 1992; Snyder et al. 2000) and fMRI (Bunge et al. 2002) that the left parietal cortex is involved in maintaining and activating motor responses on the basis of stimulus-response associations during task performance. Given the potential cognitive demands inherent in maintaining the mapping between 4 stimulus types and 4 responses, this interpretation seems a reasonable possibility.

It should be noted that the ERP results of the present paper are reported using a voltage referencing scheme of the algebraically averaged mastoids. Although this referencing scheme is fairly common, it does differ from the also commonly used average reference (i.e., where the reference is the average voltage of all the electrodes). Accordingly, we have also examined the present data using the average reference scheme, and a comparison of the 2 approaches is included in the supplementary materials (Supplementary Materials 2). The choice of the referencing scheme had little effect on the topographic distribution of the Stroop incongruency effects (although using the average reference scheme did somewhat reduce the amplitude of the effects). The close similarity in topography suggests that the relatively posterior distribution of the effects observed here likely relate to paradigmatic aspects of the design and task (including possibly the use of a manual response—cf. Liotti et al. 2000), rather than the choice of referencing scheme.

#### ***Priming and Backwards Interference versus Facilitation, Inhibition, and General Alerting Mechanisms***

In the present study our experimental focus concerned the effects of temporal separation on the processing of compatible versus incompatible stimulus components presented at different temporal delays. As already discussed, the pattern of results elicited in this design demonstrate clear interactions between SOA and stimulus incongruency, that manifest as “priming influences” in instances where the irrelevant stimulus precedes the target and “backward influences” when the irrelevant stimulus component comes later. By definition, however, those



trials that included a pretarget distractor stimulus (the task-irrelevant word) differed in form from the other SOA conditions, where the target occurred simultaneously or first. The pretarget stimulus in these conditions could have had certain consequences that complicate the interpretation of the priming influences that stem from the negative-SOA conditions. In particular, it is possible that the pretarget stimulus could have acted as an exogenous cue to alert the participant as to an impending target presentation (i.e., the target color-bar will occur within 200 ms), regardless of whether it was congruent or incongruent in meaning. This could therefore have acted to enhance processing (e.g., reduce RT values) for all the negative-SOA conditions, diluting any interference effects for the incongruent RTs and increasing the facilitation on the congruent RT values. Our results from the main experiment are, in fact, consistent with this possibility. As seen graphically in Figure 2A, a main effect of SOA was present for the congruent but not incongruent trials, with the slope of this function demonstrating a strong facilitation (lower RTs) with greater negative SOAs. Therefore, although the absolute magnitude of interference increased with earlier SOA presentations, it is unclear from these data from the main experiment alone whether these effects were driven by facilitation or interference.

Existing accounts of Stroop-task effects generally make a distinction between facilitation resulting from stimulus congruency and interference due to incongruency by contrasting performance to a semantically neutral control condition (Glaser and Glaser 1982; Dunbar and MacLeod 1984; MacLeod 1991, 1998; Tzelgov et al. 1992; MacLeod and MacDonald 2000). Due to practical signal-to-noise constraints inherent to the ERP analyses, and the large number of trial types imposed by the 5 levels of SOA in our design, we were not able to include a neutral control condition in the main experiment. However, because the distinction between stimulus compatibility and behavioral facilitation or inhibition constitutes an important processing distinction, we included a full behavioral replication of the SOA design that included a neutral reference condition. This allowed us to assess the possibility that pre-exposure of the distractor may be serving as a general exogenous alerting cue, and in turn altering the apparent contributions of facilitation and inhibition to the observed results in the main experiment.

Results from the behavioral control experiment indeed support this interpretation. The results replicate the common observation that neutral trial performance is intermediate between congruent and incongruent trial RTs. Most importantly, however, these data demonstrate that there is a main effect of SOA on the RT of the neutral trials, with the earlier SOAs facilitating the performance for the neutral trials in the same direction as the facilitation observed with the congruent trials (although not as strongly). These results therefore provide important evidence that pre-exposure of task-irrelevant stimuli were indeed serving to exert a general alerting influence that affects performance on all negative-SOA trials. Because the slope of the neutral versus SOA data is intermediate between congruent and incongruent trials, it is reasonable to interpret the SOA effects as reflecting both facilitation and inhibitory influences. To help visualize this, we presented the separate contributions of facilitation (white bars) and interference (black bars) in relation to the neutral RTs in Figure 2B. Although these behavioral results help disentangle the contribution of general alerting influences from

facilitation and interference, a net increase in the magnitude of the RT difference for earlier SOAs is still present, suggesting the presence of priming due to an exogenously cued, alerting effect, as noted above.

## Conclusion

Decision processes, such as those employed in the Stroop color-naming task, involve a cascade of operations including the sensory processing and discrimination of stimulus information, response selection, and the implementation of a final motor action plan. The present findings broaden our understanding of the temporal dynamics of neural processes resulting from stimulus incompatibility in the Stroop task. Specifically, we show that Stroop incongruency produces different functional characteristics due to pre-exposure and postexposure of task-irrelevant stimulus components. We observe that pre-exposure of an irrelevant word stimulus elicits greater RT differences and larger ERP effects, which we interpret as reflecting a form of conflict-related priming. Postexposure of the irrelevant word stimulus results in reduced RT and ERP differences, suggesting that task-irrelevant stimuli have a diminishing influence with greater delays relative to the task-relevant target. The SOA manipulation also induced corresponding changes in the onset latencies of the ERP incongruency effects presumably reflecting the time range at which the processing of the relevant and irrelevant stimulus components intersect and therefore elicit interference.

## Supplementary Material

Supplementary material can be found at: <http://www.cercor.oxfordjournals.org/>

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## Notes

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