

# An Electrophysiological Investigation of Preparatory Attentional Control in a Spatial Stroop Task

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## Abstract

■ Top-down attentional control is required when subjects must attend to one of multiple conflicting stimulus features, such as in the Stroop task. Performance may be improved when such control is implemented in advance of stimulus presentation, yet few studies have examined this issue. Our investigation employed a spatial Stroop task with a manual response, allowing us to focus on the effects of preparatory attention on verbal processing when it is the less automatic attribute. A letter cue (P or W) presented for 2200 msec instructed subjects to respond on the basis of the position or meaning of a word (up, down, left, right) placed in an incongruent position relative to center. Event-related potentials recorded during pre- and poststimulus periods were analyzed as a function of reaction time to the target stimulus

(fast vs. slow) in order to differentiate neural activity associated with more or less successful implementation of control. During the prestimulus period, fast responses to subsequent targets were associated with enhanced slow-wave activity over right frontal and bilateral central-parietal regions. During the poststimulus period, fast word trials were uniquely associated with an enhanced inferior temporal negativity (ITN) from 200 to 600 msec. More importantly, a correlation between frontal prestimulus activity and the poststimulus ITN suggested that frontal preparatory activity played a role in facilitating conceptual processing of the verbal stimulus when it arrived, providing an important link between preparatory attention and mechanisms that improve performance in the face of conflict. ■

## INTRODUCTION

The ability to voluntarily bias attention toward goal-relevant information (i.e., top-down control of attention) is an essential part of successful performance in situations where multiple stimuli or stimulus features compete for a limited set of resources (Kastner & Ungerleider, 2001; Desimone & Duncan, 1995). Within the framework of top-down attentional control, an important distinction is made between the source and sites of such control (Coull, Frackowiak, & Frith, 1998; Posner & Driver, 1992; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991). The sources of attentional control direct the allocation of attention to relevant stimulus locations or features and are thought to be subserved by neural activity in the prefrontal cortex (PFC) and parietal cortex, whereas the sites of attentional control receive modulation from the sources and are located at more posterior cortical regions responsible for perception of the relevant stimulus features (Liu, Slotnick, Serences, & Yantis, 2003; Pessoa, Kastner, & Ungerleider, 2003; Corbetta & Shulman, 2002; Corbetta, 1998; Coull et al., 1998; Desimone & Duncan, 1995; Heinze et al., 1994; Corbetta et al., 1991).

Attentional selection may be particularly important when task-irrelevant information has the potential to interfere with performance, such as in the Stroop task (Stroop, 1935). The Stroop task in its classic form requires subjects to name the ink color of words that spell a different color (e.g., the word BLUE in red ink, incongruent stimulus) or the same color (e.g., the word RED in red ink, congruent stimulus). It is consistently found that subjects exhibit slower reaction times (RTs) when naming the ink color of incongruent stimuli compared to congruent or neutral stimuli (e.g., XXX in red ink), presumably due to conflict experienced between ink color and word meaning. Whereas speed-of-processing and translation models of interference in Stroop-like tasks have emphasized conflict between competing responses (Virzi & Egeth, 1985; Morton & Chambers, 1973), more recent models have suggested that conflict may occur at earlier processing stages, such as between stimulus representations (Zhang & Kornblum, 1998; Cohen, Dunbar, & McClelland, 1990). In support of the view that conflict also arises at the stimulus level, a recent study by De Houwer (2003) using color-word Stroop stimuli found that subjects were slower to identify an incongruent color even when the responses designated by the ink color and word meaning were the same. Using the same task, van Veen & Carter (2005) replicated this behavioral effect and

additionally showed that activation in bilateral PFC and posterior parietal cortex was associated with conflict at the level of stimulus representations, consistent with results from other Stroop studies showing increased activity in the PFC and parietal cortex on incongruent trials (Badre & Wagner, 2004; Kerns et al., 2004; Liu, Banich, Jacobson, & Tanabe, 2004; Milham, Banich, & Barada, 2003; van Veen & Carter, 2002; Zysset, Muller, Lohmann, & von Cramon, 2001). Although these results suggest that the PFC and parietal cortex are involved in top-down biasing of task-relevant stimulus features, none have found direct evidence for modulation of posterior sites in relation to improved performance on the task (e.g., increase in color processing regions associated with faster responding on incongruent ink naming trials).

The majority of studies using the Stroop task have focused on the contributions of the prefrontal and parietal cortex to top-down control following stimulus presentation, leaving open the question of whether attentional control also operates prior to the onset of the target stimulus in order to reduce conflict and improve performance once the stimulus arrives. Given that conflict may occur at the level of stimulus representations, advance knowledge about the task-relevant feature may be used in order to improve performance. In one of the few Stroop studies to address this issue, MacDonald, Cohen, Stenger, and Carter (2000) presented subjects with 12-sec preparatory cues indicating to which aspect of color-word Stroop stimuli (word meaning or ink color) they should respond. Increased activity in the dorsolateral prefrontal cortex (DLPFC) during this preparatory period was negatively correlated with subjects' interference scores (i.e., difference in RT between incongruent and congruent trials), a finding the authors suggest reflects an increase in the engagement of top-down processes prior to conflict presentation. However, it is not clear whether this increase in DLPFC activity reflects the top-down biasing of specific stimulus features or a less selective process, such as vigilance or general anticipatory attention, given that activity in posterior cortical regions processing word meaning or color information was not reported.

An event-related potential (ERP) study also using a cued color-word Stroop task identified an occipital-parietal negative slow wave during the preparatory period that differentiated correct from incorrect trials, the origin of which was localized to the extrastriate cortex with only a minor contribution from the DLPFC (West, 2003). Because this slow wave was the same for both color and word cues, the author suggested that it reflected activation of nonselective neural processes supporting correct responding rather than selection of task-relevant stimulus attributes. However, an alternative possibility is that the slow wave reflected the activation of posterior sites involved in processing the task-relevant attribute in each condition (i.e., color or word), but that differences between these conditions could not be

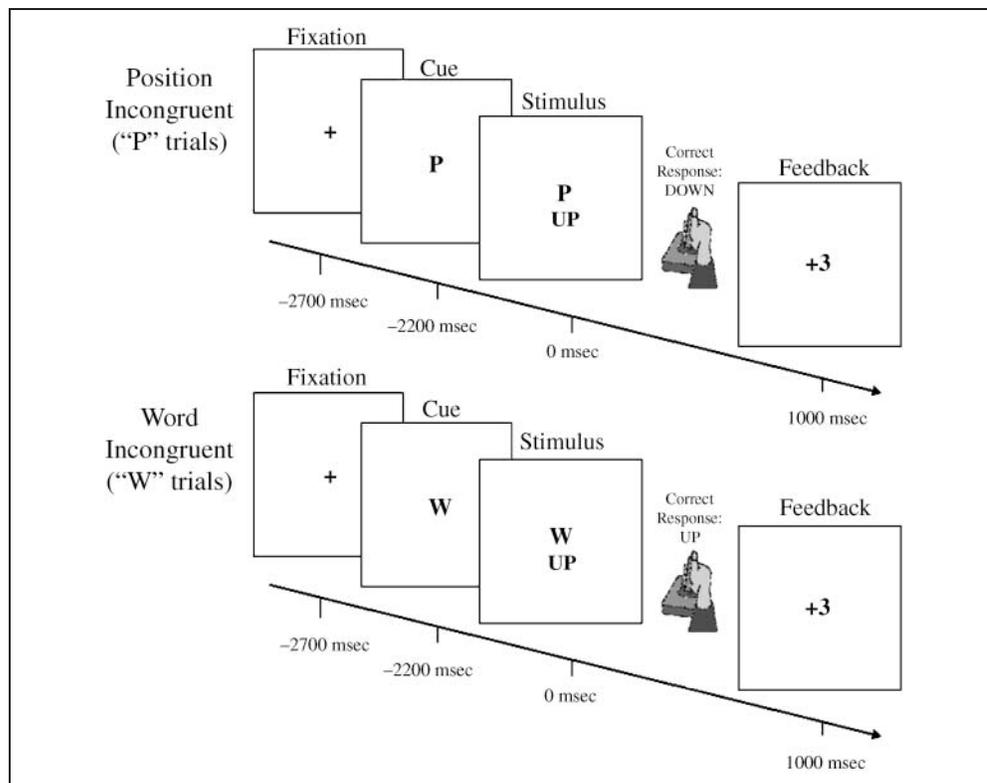
adequately distinguished due to the relatively low spatial resolution of EEG. This discrepancy between results obtained by MacDonald et al. (2000) and West (2003) warrants further investigation into the frontal contribution to preparatory attentional control prior to conflict stimuli. Furthermore, although the relationship between prestimulus neural activity and behavior was examined, neither study explicitly investigated the relationship between pre- and poststimulus activity. Thus, it remains unclear how neural processes underlying advance selection of task-relevant stimulus features might impact activity associated with processing the conflict stimulus when it arrives.

We examined ERPs recorded during a cued spatial Stroop task to address the following questions: (1) Is activity at the source and sites of attentional control during a preparatory period related to successful performance? (2) What is the nature of the relationship between neural activity during the preparatory period and that elicited by conflict stimuli?

In our task, letter cues were presented for 2200 msec prior to the onset of each target stimulus (a direction word in a position around the center). These cues informed subjects whether they would need to make a manual response on the basis of the spatial location or the meaning of the target word, providing subjects with the opportunity to engage top-down attentional processes that could enhance performance ahead of time (see Figure 1). ERPs are particularly well suited to such an investigation given their excellent temporal resolution, which enables both the characterization of sustained effects occurring during prestimulus periods (e.g., Brunia & van Boxtel, 2001) and the isolation of attentional effects on the early processing of stimulus features (e.g., Mangun & Hillyard, 1995).

Correct manual responses on incongruent trials were segregated into those with relatively fast RTs (below the median RT for each subject) and relatively slow RTs (above the median RT for each subject). Thus far, the majority of Stroop studies have limited their analyses of control implementation to differences that emerge in neural activity between congruent and incongruent trials (e.g., Kerns et al., 2004; Banich et al., 2000; West & Alain, 1999, 2000). Recently, a few have additionally examined RT variability within incongruent trials as a function of whether the preceding trial was congruent (cI) or incongruent (iI). Generally, these studies have found that subjects exhibit faster RTs on iI as compared to cI trials, presumably because attentional control recruited on incongruent trial  $n-1$  leads to a reduction in conflict and speeding of RT on incongruent trial  $n$  (Egner & Hirsch, 2005; Kerns et al., 2004; Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). Thus, in line with the view that the implementation of attentional control is a dynamic process, we have chosen to examine control success as a function of the variability in RT among blocks of incongruent trials.

**Figure 1.** Examples of position (“P”) and word (“W”) incongruent trial types. In the actual experiment, “W” was presented in green font and “P” was presented in orange font. Onset times of fixation and cue are indicated relative to the onset of the target stimulus.



We predict that preparatory activation of the sources of top-down control should result in an increase in sustained preparatory potentials over prefrontal and parietal regions beginning shortly after the cue and leading up to target presentation. As increases in top-down control should lead to faster responding, these preparatory potentials should be modulated by later RT to conflict stimuli. In addition, to the extent that preparatory attention may involve biased processing of the task-relevant features of upcoming conflict stimuli, we might also expect to find an increase in prestimulus activity at posterior sites processing those features when RT to stimuli is faster. To this aim, we will specifically examine activity at inferior temporal electrodes on trials where subjects respond according to word meaning, as this region has been associated with conceptual processing of verbal stimuli (Marinkovic 2004; Mangels, Picton, & Craik, 2001; Price, 1998; Demonet et al., 1992). It may be particularly useful to focus on these word trials given evidence that responding according to word meaning in the spatial Stroop is more effortful than responding according to spatial information, particularly when a manual response is used (Baldo, Shimamura, & Prinzmetal, 1998; Lu & Proctor, 1995; Virzi & Egeth, 1985). Although it is likely that effects at the sites of spatial processing would occur on trials in which subjects attend to spatial location, the limited spatial resolution of EEG does not allow us to distinguish between parietal regions involved in processing spatial information about targets (sites) and those involved in the implementation

of top-down control (source) either prior to or during stimulus presentation.

In addition to prestimulus activity, we examined neural activity time-locked to the onset of the incongruent stimulus as a function of RT, as it has been suggested that advance preparation may improve performance by enhancing the activity of neurons processing task-relevant features once stimuli are actually presented (Pessoa et al., 2003; Hopfinger, Buonocore, & Mangun, 2000). Thus, in addition to investigating the effects of preparation on early visual responses that are influenced by spatial attention (P1/N1)(Anllo-Vento, Schoenfeld, & Hillyard, 2004; Herrmann & Knight, 2001; Hillyard & Anllo-Vento, 1998; Mangun & Hillyard, 1995), we examined the effects of preparation on the amplitude of a waveform that has been previously recorded from inferior temporal electrodes and is associated with semantic processing of verbal stimuli (Marinkovic, 2004; Butterfield & Mangels, 2003; Mangels et al., 2001; Nobre, Allison, & McCarthy, 1994), what we refer to here as the inferior temporal negativity (ITN). This waveform starts as early as 200 msec, peaks at approximately 320–340 msec, and has also been shown to be influenced by attention (Mangels et al., 2001). We predict that the ITN will not only be greater on trials in which subjects are cued to attend to semantic content of words (“W” trials), but that it will be enhanced further when subjects process that content quickly and accurately (i.e., faster RTs on correct trials). Moreover, to the extent that the effectiveness of preparatory control is directly

responsible for modulating the ITN, we should see a direct relationship between the underlying neural activity in the pre- and poststimulus periods.

## METHODS

### Subjects

Eighteen people (9 men and 9 women) recruited from the Columbia University area participated in the experiment. All subjects were right-handed, had normal or corrected-to-normal vision, were native speakers of English, and were between the ages of 18–35 (mean age 21.8 years). All subjects provided informed consent in accordance with Columbia University Institutional Review Board regulations.

### Design and Procedure

In the cued spatial Stroop task, subjects respond according to spatial or semantic properties of target stimuli. Targets consisted of a direction word (“up,” “down,” “right,” or “left”) presented in a location relative to center that was different (incongruent trials) or the same (congruent trials) as word meaning. Examples of incongruent trial types can be seen in Figure 1. Each trial began with a centrally presented crosshair from –2700 to –2200 msec (500 msec length of presentation), which was then replaced by a letter cue designating whether subjects should respond to upcoming stimuli on the basis of the position (orange letter “P”) or word meaning (green letter “W”). Cues were presented in color to increase their overall salience and differentiation from each other.

To minimize working memory load, the cue remained on-screen for the full 2200 msec preparatory period, followed immediately by addition of the target stimulus in a position around the cue. Subjects were instructed to respond to the target by moving a joystick as quickly and as accurately as possible, after which they were given feedback in the form of a positive or negative score based on accuracy and speed of RT. Subjects received a “–3” if they were incorrect and between “0” and “+5” if they were correct, with faster RTs yielding greater positive values. The trial ended with a blank screen for 500 msec, after which a crosshair signaled the start of a new trial.

Subjects completed 13 blocks of 48 trials each. Three blocks were “mixed” blocks in that they contained 24 trials where the meaning and spatial position of the word were different from each other (incongruent trials) and 24 trials in which the meaning and spatial position of the word were the same (congruent trials). Mixed blocks were presented at the first, seventh, and last block (144 trials in total). The remaining 10 blocks were “all-incongruent” blocks, containing only incongruent trials (480 trials in total) in order to maximize the

opportunity to separate neural activity associated with fast and slow responses to conflict stimuli. Although incongruent trials were of primary interest for the ERP analysis, mixed blocks were important for the behavioral analyses of Stroop conflict. Specifically, performance on congruent and incongruent trials in the mixed blocks were used as a point of comparison from which to evaluate whether subjects demonstrated typical slowing of RT on incongruent trials in all-incongruent blocks. Subjects were informed that the majority of blocks would contain only incongruent stimuli.

There were 12 different types of incongruent trials that could be presented to subjects [4 (words) × 3 (incongruent spatial positions)]. In addition, because each stimulus type could be preceded either by a W cue or a P cue, there were a total of 24 different possible incongruent trial types. Each trial type was randomly presented twice during the block for a total of 20 times across all 10 all-incongruent blocks. In the mixed blocks, subjects were presented with an additional four stimulus configurations for congruent trials (the word “up” above the center, the word “down” below the center, the word “left” to the left of center, and the word “right” to the right of center). The ratio of congruent to incongruent trials was equal within these blocks such that subjects received 24 trials each for congruent and incongruent conditions.

### ERP Acquisition and Analysis

Continuous EEG was recorded using a 64-electrode Quick-Cap (Compumedics Inc., El Paso, TX). EEG was amplified with Neuroscan (El Paso, TX) SYNAMPS, and digitized at a rate of 500 Hz with a band pass of DC to 100 Hz. Inter-electrode impedance was kept below 11 k $\Omega$ . Eye movements and blinks were recorded from electrodes located 1 cm lateral to the outer canthi (LO1/LO2) and over the infraorbital ridge (IO1/IO2), as well as in-between these electrodes (F9/F10). EEG was initially referenced to Cz during recording, then re-referenced to the average offline. Eye blinks and movements were corrected in the continuous EEG using ocular source components that were derived using BESA v5.1 (Scherg and Berg, 1995; Lins, Picton, Berg, & Scherg, 1993).

Correct trials were averaged according to cue type (position, word) and RT (fast, slow). Only trials from the all-incongruent blocks were used, as there were too few trials in the mixed blocks for adequate analysis when segregating trials based on median RT. Trials were collapsed across the 12 different incongruent [4 (word) × 3 (position)] conditions. For analysis of the prestimulus (preparatory) period, we chose an epoch encompassing the full 2200 msec prior to Stroop stimulus presentation. For analysis of the poststimulus (target) period, we chose an epoch encompassing 600 msec after stimulus presentation. Prestimulus and poststimulus epochs were

corrected to a 100-msec baseline prior to the cue and target, respectively.

Each trial was categorized as either fast or slow based on the median RT for each subject. All trials falling above the median RT for a given subject were designated “slow,” whereas all those falling below the median were designated “fast.” In order to compensate for general speeding or slowing of RT that may occur across the entire length of the experiment as the result of learning or fatigue, respectively, the median RT used to categorize trials was calculated separately for the first and second half of the experiment. After artifact rejection (trials with excessive muscle noise, slow wave drift, or activity with an amplitude of  $\pm 100$  mV), an average of 96 (range 52–111) fast incongruent position trials, 95 (range 54–110) fast incongruent word trials, 92 (range 46–112) slow incongruent position trials, and 93 (range 55–110) slow incongruent word trials remained for each subject.

All effects were analyzed with repeated measures analyses of variance (ANOVAs) using RT (fast vs. slow), cue (position vs. word on current trial), hemisphere, and electrode as factors.<sup>1</sup> For electrophysiological data, main effects will not be discussed if qualified by interactions other than with the electrode factor. For effects involving the electrode factor, only those in which electrode interacts with significant main effects or other interactions will be reported.

Our investigation of the sources of top-down attention during the preparatory period focused on electrode groups encompassing frontal and parietal regions, in line with the prediction that activity in these underlying cortical regions would be related to implementation of top-down control. These electrode groups consisted of a midfrontal (AF7/8, F5/6, and F7/8) and a superior frontal group (FP1/2, AF3/4, F3/4) located proximally to the middle and superior frontal gyri, respectively. Additionally, a central-parietal (C3/4, CP1/2, CP3/4) and parietal group (P3/4, P5/6, PO3/4) were selected for analysis. Finally, to investigate activity located at the sites of semantic processing, a group of inferior temporal electrodes located proximally to the ventral visual stream (FT9/10, T7/8, TP7/8) were also included. As the examination of sustained neural activity prior to target presentation was of primary interest, we analyzed mean amplitude of the waveform from 700 msec prior to target onset until stimulus presentation (–700 to 0 msec), in 250-msec time bins (excepting the last bin, which was 200 msec).

Analyses of the P1 and N1 waveforms were based on peak amplitudes at their P5/6 maximum. For each subject, peak latency of the P1 was based on the maximum positive peak at electrode P6 (right-hemisphere parietal) between 50 and 150 msec poststimulus, and peak latency of the N1 was based on the maximum negative peak at electrode P5 (left-hemisphere parietal) between 130 and 230 msec. However, subsequent analy-

ses of the P1 and N1 included amplitudes at all electrodes in the parietal group (P3/4, P5/6, PO3/4) in order to obtain a more stable estimate of regional neural activity. To investigate activity associated with semantic processing after conflict stimulus presentation, a group of inferior temporal electrodes (FT9/10, T7/8, TP7/8, TP9/10) was analyzed from 200 to 400 and 400 to 600 msec following stimulus presentation. The inclusion of electrodes TP9/10 allowed for a more extensive characterization of the data in the poststimulus period, as they exhibited the same pattern of activity as the other inferior temporal electrodes (FT9/10, T7/8, TP7/8).

Finally, to ensure that pre- and poststimulus neural activity was not markedly different for mixed and all-incongruent blocks, we collapsed over RT and compared the amplitude of the waveforms at any electrode groups and time periods that differed in the primary analyses. For the prestimulus period, all trials in the mixed blocks were compared to all trials in the all-incongruent blocks, given that in the preparatory period, participants did not know what the status of the upcoming trial would be (congruent or incongruent). For the poststimulus period, only incongruent trials in the mixed blocks were compared with trials in the all-incongruent blocks.

All statistics were performed on scalp-recorded amplitude values. However, definitive conclusions concerning localization of neural sources are difficult to make using scalp-recorded potentials. In order to improve our ability to identify the source of waveforms, we have presented current source density (CSD) maps of surface Laplacian potentials alongside traditional topographical spline maps, as it has been shown that surface Laplacian potentials likely reflect activity from superficial cortical sources underneath or very close to the recording electrode (Srinivasan, 2005).

Greenhouse–Geisser corrections (Greenhouse & Geisser, 1959) were applied where appropriate. Significant main effects and interactions were followed by Tukey’s honestly significant difference (HSD) tests. Only comparisons significant at an alpha level of .05 are reported.

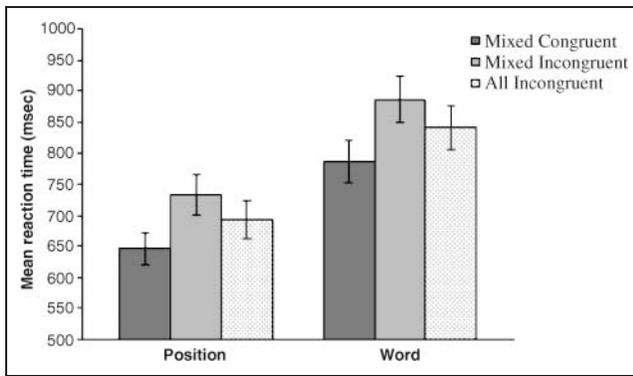
## RESULTS

### Behavioral Data

Mean RT data for all trial types can be found in Figure 2.

#### *Mixed Blocks*

RT to congruent trials was significantly faster than RT to incongruent trials, as indicated by a main effect of congruency,  $F(1,17) = 125.79, p < .0001$ , in a 2 (incongruent vs. congruent)  $\times$  2 (position vs. word) ANOVA. There was also a main effect of cue type such that RT was significantly faster on position trials than on word



**Figure 2.** Mean RT on congruent and incongruent trials during mixed blocks and incongruent trials during all incongruent blocks, segregated for position and word trials. Error bars in this and all subsequent figures represent the standard error of the mean (*SEM*).

trials,  $F(1,17) = 46.2, p < .0001$ . There was no interaction between cue type and congruency.

### Incongruent Blocks

Subjects had significantly faster RTs for incongruent position trials as compared with incongruent word trials in the all-incongruent blocks,  $t(17) = 12.41, p < .01$ , consistent with results obtained in the mixed blocks. Although incongruent trials in the all-incongruent blocks were significantly faster than incongruent trials in the mixed blocks (767.4 vs. 810.2 msec),  $t(17) = 2.9, p = .01$ , it is important to note that RTs on all-incongruent trials were still significantly slower than congruent trials (689.8 msec),  $t(17) = 3.1, p < .01$ , thus confirming that conflict was present even in the all-incongruent blocks.

Subjects made errors on less than 10% of trials. There was no overall difference in the number of errors made on word versus position trials ( $p > .2$ ). However, there was a main effect of RT,  $F(1,17) = 13.92, p < .01$ , and an interaction between cue type (word vs. position) and RT (fast vs. slow),  $F(1,17) = 13.26, p < .01$ . Both of these effects were in the opposite direction than would be expected if there were a speed-accuracy trade-off. There were significantly more errors on slow position trials ( $M = 9.06, SEM = 2.05$ ) as compared to fast position trials ( $M = 0.78, SEM = .27$ ), whereas there was no difference between slow ( $M = 4.5, SEM = 1.09$ ) and fast word trials ( $M = 3.2, SEM = .66$ ).

## Electrophysiological Data

### Prestimulus (Preparatory) Period

From  $-700$  to  $0$  msec there was an interaction between electrode group (superior frontal, midfrontal, central-parietal, parietal, inferior temporal), hemisphere, and RT:  $-700$  to  $-450$  msec:  $F(4,68) = 3.8, p < .02, \epsilon =$

.799;  $-450$  to  $-200$  msec:  $F(4,68) = 4.9, p < .005, \epsilon = .759$ ;  $-200$  to  $0$  msec:  $F(4,68) = 4.8, p < .005, \epsilon = .812$ . Thus, we analyzed each group individually in a four-way ANOVA with RT (fast vs. slow), Cue Type (position vs. word), Hemisphere, and Electrode (three per group) as factors.

### Frontal Electrodes

No significant main effects or interactions were found at the superior frontal electrode group (FP1/2, AF3/4, F3/4). However, for the midfrontal group of electrodes (AF7/8, F5/6, F7/8) (see Figure 3A), there was an interaction between RT and hemisphere from  $-700$  to  $0$  msec prestimulus [ $-700$  to  $-450$  msec:  $F(1,17) = 5.36, p < .05$ ;  $-450$  to  $-200$  msec:  $F(1,17) = 8.29, p = .01$ ;  $-200$  to  $0$  msec:  $F(1,17) = 8.86, p < .01$ ], with post hoc analyses indicating that fast trials were more positive than slow trials only over the right hemisphere. In addition, an interaction between hemisphere and cue type was found between  $-700$  and  $0$  msec [ $-700$  to  $-450$  msec:  $F(1,17) = 10.3, p = .005$ ;  $-450$  to  $-200$  msec:  $F(1,17) = 10.3, p = .005$ ;  $-200$  to  $0$  msec:  $F(1,17) = 7.1, p < .05$ ], with post hoc analyses indicating that amplitude of the waveform was greater for word trials than for position trials on the right hemisphere only between  $-700$  and  $-200$  msec.

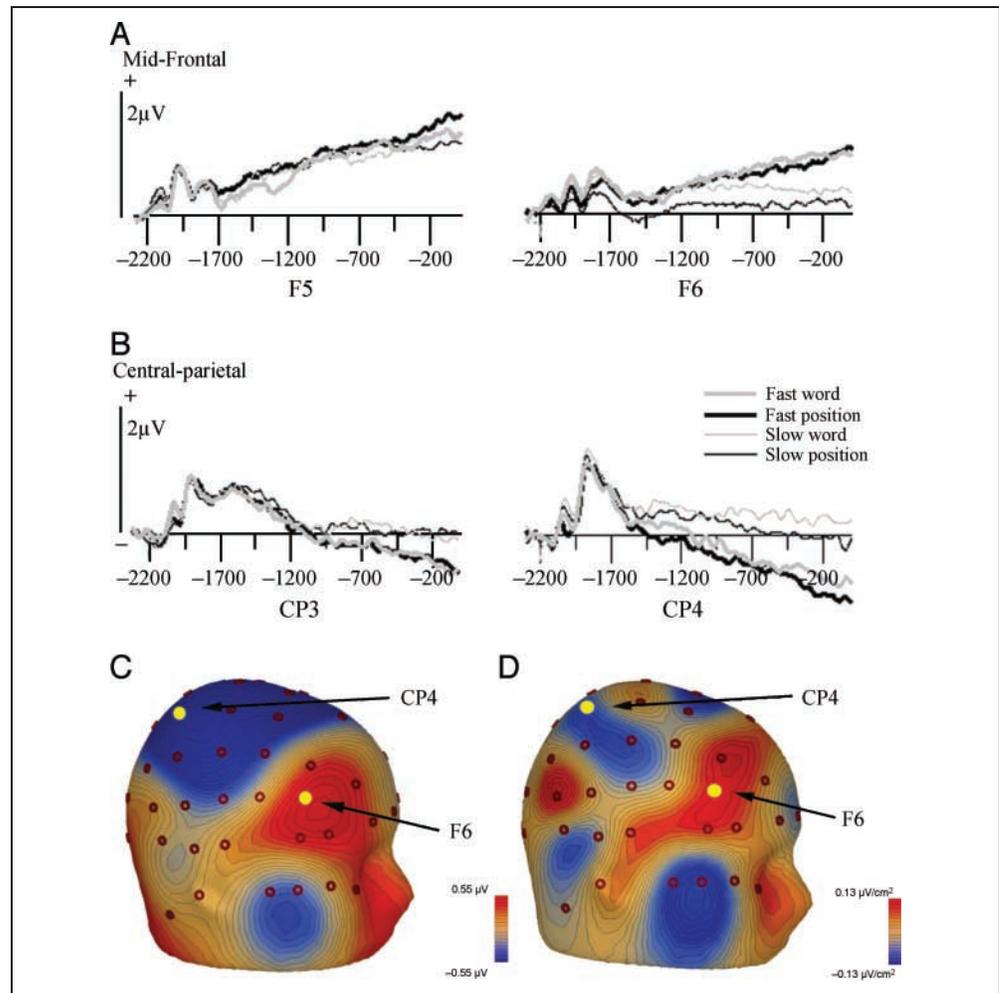
### Central-Parietal and Parietal Electrodes

Differences in activity among fast and slow trials were found across widespread areas of the posterior scalp. Although significant effects were not found for the parietal group, significant differences between fast and slow trials were found for the central-parietal group (C3/4, CP1/2, CP3/4) (see Figure 3B). For these negative-going central-parietal waveforms, there was significantly greater negativity for fast trials as compared to slow trials between  $-700$  to  $0$  msec:  $-700$  to  $-450$  msec,  $F(1,17) = 28.8, p < .001$ ;  $-450$  to  $-200$  msec,  $F(1,17) = 37.3, p < .001$ ;  $-200$  to  $0$  msec,  $F(1,17) = 40.67, p < .001$ . Topographic distribution of activity selective to fast trials at  $-50$  msec is shown in Figure 3C, highlighting a right frontal positivity and broad central-parietal negativity. CSD mapping of this activity suggests that frontal and central-parietal activity represent two separate cortical dipole sources (Figure 3D).

### Inferior Temporal Electrodes

Effects found at the inferior temporal (IT) electrode group (FT9/10, T7/8, TP7/8) (not shown) were inconsistent across the prestimulus epoch, but overall did not provide strong evidence of preparatory semantic processing during word trials. Fast trials were more positive

**Figure 3.** (A) Grand-average waveforms at electrodes F5 (left hemisphere) and F6 (right hemisphere). (B) Grand-average waveforms at electrodes CP3 (left hemisphere) and CP4 (right hemisphere). (C) Mean scalp-recorded amplitude map illustrating the difference waveform of fast trials minus slow trials (collapsed over position and word cues) at  $-50$  msec. (D) CSD map of difference waveform shown in mean amplitude map, suggesting the presence of separate cortical sources for midfrontal and central-parietal effects.



than slow trials,  $F(1,17) = 8.9$ ,  $p < .01$ , between  $-700$  and  $-450$  msec. This effect was qualified by a significant interaction between electrode and RT,  $F(2,34) = 8.5$ ,  $p = .001$ ,  $\epsilon = .906$ , indicating that the greatest difference between fast and slow trials occurred at electrodes FT9/10 (although mean amplitude values indicated that fast trials were greater than slow trials at all three electrodes in the IT group). Then, later in the epoch ( $-450$  and  $0$  msec), a Hemisphere  $\times$  Cue Type interaction emerged:  $-450$  to  $-200$  msec,  $F(1,17) = 5.39$ ,  $p < .05$ ;  $-200$  to  $0$  msec,  $F(1,17) = 5.21$ ,  $p < .05$ . However, the only differences to reach significance in post hoc comparisons occurred between  $-450$  to  $-200$  msec over the right hemisphere, where word trials elicited greater positivity than position trials. During these periods, there were no main effects of RT or interaction of RT with the other factors.

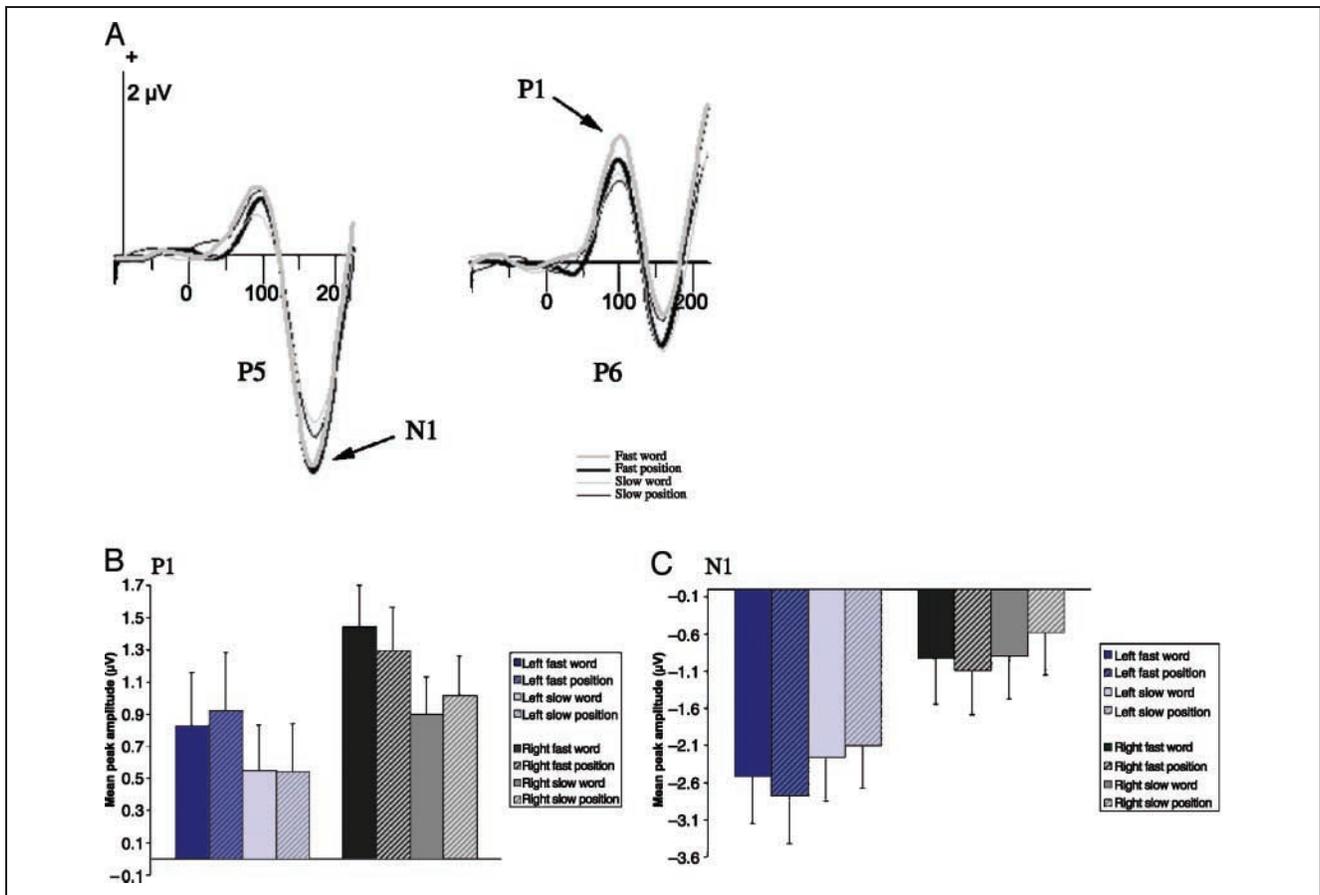
#### Poststimulus Period

**P1 and N1 waveforms.** As can be seen in Figure 4, the peak of the P1 was greater on the right than on the left hemisphere [main effect of hemisphere:  $F(1,17) = 6.99$ ,  $p < .05$ ], with the effect being largest at electrodes P5/6

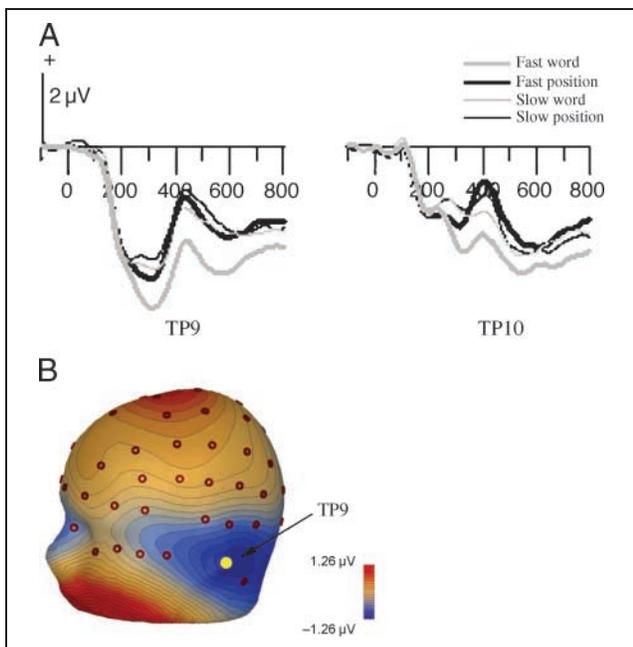
[Hemisphere  $\times$  Electrode:  $F(1,17) = 15.8$ ,  $p < .001$ ]. In addition, the P1 was enhanced for fast trials as compared to slow trials, as evidenced by a main effect of RT,  $F(1,17) = 5.8$ ,  $p < .05$ . The P1 was not significantly influenced by cue type, nor was there an interaction between cue type and RT.

For the peak of the N1, which was larger over the left hemisphere,  $F(1,17) = 12.6$ ,  $p < .005$ , an interaction between cue type and RT was found,  $F(1,17) = 10.1$ ,  $p < .01$ . Although the N1 was numerically greater on fast as compared to slow trials for both position and word cue types, these differences only reached significance on position trials.

**Inferior temporal electrodes.** As shown in Figure 5, between  $200$  and  $600$  msec poststimulus, amplitude of fast word trials was more negative than all other trial types as evidenced in an interaction between RT and cue type [ $200$  to  $400$ :  $F(1,17) = 8.5$ ,  $p = .01$ ;  $400$  to  $600$ :  $F(1,17) = 6.7$ ,  $p < .05$ ] and confirmed in post hoc comparisons between fast word trials and slow word, fast position, and slow position trials. From  $200$  to  $400$  msec, the waveform was more negative-going on left than on the right,  $F(1,17) = 24.9$ ,  $p < .001$ . There was no



**Figure 4.** (A) Grand-average waveforms illustrating P1 and N1 components at P5/6. Note that statistics were performed on peak amplitudes for each individual subject, illustrated in (B) and (C). (B) Mean amplitude of P1 component based on hemisphere, RT, and cue (see Methods for details). (C) Mean amplitude of N1 component based on hemisphere, RT, and cue (see Methods for details).



**Figure 5.** (A) Grand-average waveforms illustrating the ITN at TP9/10. (B) Mean scalp-recorded amplitude map illustrating the difference waveform of fast word trials minus slow word trials at 300 msec posttarget.

interaction between this hemisphere effect and the other factors.

#### *Relationship between Pre- and Poststimulus Neural Activity*

To investigate the relationship between advance preparation and subsequent processing of conflict stimuli, we examined correlations between the prestimulus and poststimulus activity that had significantly differentiated fast and slow responses. To ensure that any overall differences in baseline amplitude between subjects did not drive correlation data, difference waves were created by subtracting the amplitude of the waveform on slow trials from that on fast trials.

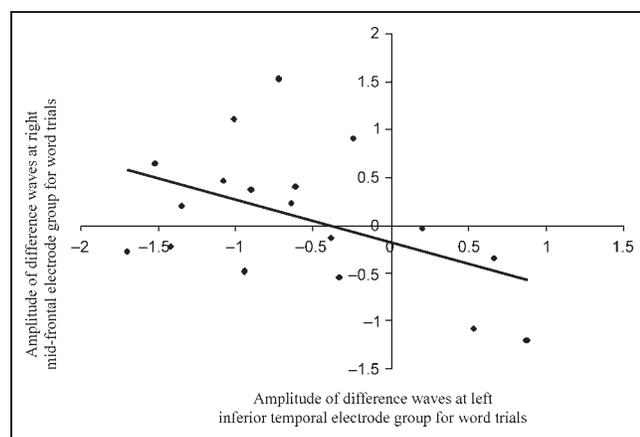
For the prestimulus period, we analyzed the right mid-frontal, left central-parietal, and right central-parietal group of electrodes, averaged across the entire end of the preparatory epoch ( $-700$  to  $0$  msec prior to the target stimulus). For the poststimulus period, we analyzed the left and right parietal group of electrodes at peak amplitude for both the P1 and N1 waveforms, as well as the inferior temporal group of electrodes

separately from 200 to 400 and 400 to 600 msec. All correlations were performed separately for position and word trials (i.e., difference waves for prestimulus word trials were correlated only with difference waves for poststimulus word trials, and vice versa for position trials).

There were no significant correlations between prestimulus activity at right midfrontal or left or right central-parietal electrodes and the poststimulus P1 or N1 for either position or word trials. However, as can be seen in Figure 6, a significant negative correlation was found between prestimulus activity at right midfrontal electrodes and poststimulus activity at left inferior temporal electrodes on word trials between 200 and 400 msec poststimulus ( $r = -.499, p < .05$ ). During the 400- to 600-msec poststimulus interval, the correlation was in the same direction but did not reach statistical significance ( $p = .085$ ). The negative direction of the correlation indicates that subjects showing greater positivity for fast trials as compared to slow during the prestimulus period (greater positive difference wave values) also exhibited greater negativity for fast as compared to slow trials after stimulus presentation (greater negative difference wave values). As would be expected if the ITN were specific to verbal processing, no relationship between activity at prestimulus frontal and poststimulus inferior temporal electrodes was found on position trials. Furthermore, no significant correlations were found between activity at prestimulus central-parietal and poststimulus inferior temporal electrodes for either word or position trials.

#### Comparison of Mixed and All-incongruent Blocks

For the prestimulus analyses, there were no significant differences between amplitude of waveforms on trials



**Figure 6.** Scatterplot showing the relationship between amplitude of difference waves at prestimulus right midfrontal electrodes (y axis) and poststimulus left inferior temporal electrodes (x axis) for word trials.

in the mixed and all-incongruent blocks between  $-700$  and  $0$  msec at middle frontal electrodes. No differences were found between  $-700$  and  $-450$  and  $-200$  and  $0$  msec at central-parietal electrodes. However, at these electrodes there was a trend towards greater negativity among all-incongruent trials between  $-450$  and  $-200$  msec ( $p = .052$ ), suggesting that certain aspects of control may be somewhat increased when conflict is present on all trials, similar to findings from studies of conflict adaptation (Botvinick et al., 1999). During the poststimulus period, there were no differences between incongruent trials in the mixed and all-incongruent blocks at the electrode groups and periods analyzed in the primary analyses (P1, N1, and ITN). These results suggest that perceptual and conceptual processing of the target was not significantly influenced by whether it was presented in the context of all incongruent trials or mixed congruent and incongruent trials.

## DISCUSSION

In an ERP study using a cued spatial Stroop task, we sought to investigate whether activity at the source and sites of attentional control during a preparatory period was related to improved behavioral performance in the form of relatively fast RT to conflict stimuli. Furthermore, we examined the nature of the interaction between pre- and poststimulus neural activity in relation to RT. Our results indicate that increases in activity at right midfrontal and bilateral central-parietal regions during a preparatory interval are associated with faster RT to spatial Stroop stimuli. Although one cannot directly infer source location from topographical distribution, the CSD map supports the view that activity in these regions reflects, in part, cortical sources in a frontal-parietal network.

We did not find activity at inferior temporal regions on word trials that was indicative of preparatory attentional biasing of the sites of semantic processing; however, results revealed a bilateral negativity in this area occurring poststimulus that was significantly greater on fast word trials than other trial types. In addition, on word trials only, there was a relationship between prestimulus activity at right midfrontal electrodes and poststimulus activity at left inferior temporal electrodes. Thus, it appears that those subjects who demonstrated greater top-down control during the preparatory period (in the form of greater right frontal positivity) also show an enhanced neural response in regions associated with semantic processing (in the form of an enhanced left ITN) when word is the task-relevant stimulus feature. Together, these findings suggest that top-down attentional control during a preparatory period may recruit a network of frontal and parietal areas, particularly in the right midfrontal cortex, that bias activity in task-relevant

processing regions, thereby leading to improved behavioral performance in response to conflict stimuli.

### **Preparatory Activity Associated with Faster Responding to Conflict**

A decrease in response time in the presence of conflict was associated with an increase in the amplitude of sustained potentials occurring during the preparatory period at right midfrontal and bilateral central-parietal electrodes. Our results are consistent with previous research implicating activity in the prefrontal and parietal cortex as the source of top-down attentional control (Brass & von Cramon, 2004; Kerns et al., 2004; Giesbrecht, Woldorff, Song, & Mangun, 2003; Liu, Slotnick, et al., 2003; Pessoa et al., 2003; Corbetta & Shulman, 2002; Hopfinger et al., 2000; MacDonald et al., 2000; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; Desimone & Duncan, 1995; Corbetta et al., 1991). The frontal effect in particular may reflect activation of the source of biasing signals, given the correlation found between activity at right frontal and left inferior temporal electrodes for word trials. The location of our frontal activity is similar to that found in other studies using the Stroop task (Kerns et al., 2004; MacDonald et al., 2000), but more anterior to those reported in studies examining preparatory attentional control in nonconflict tasks (Corbetta & Shulman, 2002; Kastner & Ungerleider, 2001). This may result from the relatively more complex nature of our task, as it has been suggested that more anterior regions of the PFC are involved in attentional control under increasing levels of uncertainty (Pollmann, 2004) or processing complexity (Koechlin, Ody, & Kouneiher, 2003).

The right lateralization of the effect is consistent with studies indicating that the right prefrontal cortex in particular is involved in attentional selection and/or task preparation (Kerns et al., 2004; Sohn, Ursu, Anderson, Stenger, & Carter, 2000), but is in contrast to results obtained by MacDonald et al. (2000), who found that activity in the left DLPFC during a preparatory period correlated negatively with interference scores in a cued color-word Stroop task. In our task, left-hemisphere midfrontal ERPs did not differ significantly based on cue type or RT. However, the mean amplitude at left midfrontal electrodes was greater for all trial types than for right midfrontal electrodes on slow word trials. Thus, it is possible that verbal encoding and maintenance of the letter cue recruited left-hemisphere frontal regions in our task (Smith & Jonides, 1999; Heil, Rosler, & Hennighausen, 1997) and that the relatively higher linguistic content of the whole word cues used by MacDonald et al. resulted in an increased left-hemisphere predominance of activity during the preparatory period.

Preparatory activity at right frontal regions was found to be significantly greater for word trials as compared to position trials, regardless of RT. Given findings indicating that conceptual processing of word meaning is more

effortful than spatial processing in the spatial Stroop task (Baldo et al., 1998; Lu & Proctor, 1995; Virzi & Egeth, 1985), this difference may reflect the greater need for top-down control on these more difficult trials. Consistent with the notion, MacDonald et al. (2000) found greater DLPFC activity during a preparatory period on the more effortful color naming trials as compared to word reading trials in their color-word Stroop task.

There was no consistent pattern of effects in the ERP data obtained at inferior temporal regions during the preparatory period. Although this variability makes interpretation of results difficult, there did not seem to be clear evidence of preparatory modulation at the sites of semantic processing in our task. This is in contrast to several functional magnetic resonance imaging (fMRI) studies that found increased activity in areas of extrastriate cortex that process to-be-attended stimulus locations or features prior to presentation of nonconflicting stimuli, also referred to as “baseline shifts” (Luks & Simpson, 2004; Chawla, Rees, & Friston, 1999; Kastner et al., 1999; Luck, Chelazzi, Hillyard, & Desimone, 1997). It is possible that modulation at the sites of semantic processing was not detectable because changes in oscillatory activity within IT regions were not phase- and/or time-locked to the onset of the cue, but would nevertheless influence processing once target stimuli are presented.

By this logic, such baseline shifts would be more apparent in the induced EEG, which can detect changes in oscillatory power that are not phase-locked to the onset of a particular stimulus. Interestingly, Tallon-Baudry, Bertrand, Henaff, Isnard, and Fischer (2005) recently found an increase in induced gamma band activity with attention in lateral occipital regions during a preparatory period before presentation of novel objects. When the objects were then presented, attention increased gamma band activity in the fusiform gyrus but not lateral occipital regions. These results were interpreted as preparatory baseline shifts in early sensory regions (lateral occipital cortex), leading to faster processing downstream in the fusiform gyrus when object stimuli were presented. Consistent with this interpretation, it is possible that more complex conceptual processing of word meaning in our task can only be performed once words are actually presented, and that biasing during the preparatory period has an impact on earlier sensory processing regions.

An alternative explanation of our findings may be that increases in prestimulus activity at frontal and central-parietal regions associated with decreased RT reflect the engagement of general vigilance or anticipatory mechanisms rather than top-down biasing of regions processing task-relevant features. Previous studies have identified networks involving the right DLPFC as being involved in general vigilance or arousal (Cabeza & Nyberg, 2000; Coull, 1998). Furthermore, modulation of neural activity at the sites of attentional control was

not reported by MacDonald et al. (2000), making it difficult to determine whether the DLPFC activity found in that study is related to preparatory biasing of posterior regions or general vigilance/anticipation processes. Nevertheless, the correlation we found between prestimulus right frontal and poststimulus left IT activity on word trials is more consistent with a feature-specific biasing account of the data.

### **Poststimulus Activity Associated with Faster Responding to Conflict**

After presentation of conflict stimuli, we found that amplitude of the visually evoked P1/N1 waveforms differed as a function of RT. Fast trials exhibited greater activity than slow trials for both the P1 and N1 waveforms, independently of whether subjects were attending to word meaning or spatial location. Given that RT will be partially dependent on selective attention, these results are consistent with previous research suggesting that the amplitude of these early potentials increases with greater spatial attention to a visual stimulus (Hillyard & Anllo-Vento, 1998). As all stimuli were presented in varying spatial locations, it is likely that greater spatial orienting to target stimuli would decrease RT regardless of whether position or word information is ultimately selected. However, whereas the bulk of cognitive processing on position trials may be accomplished by spatial orienting to stimuli, word trials additionally require conceptual processing of word meaning after spatial attention has been oriented to the target.

Confirming our predictions, we found a greater ITN in response to target stimuli between 200 and 600 msec for fast word trials as compared to slow word and position trials. These results are particularly compelling considering that all target stimuli contained both semantic and spatial properties, yet the neural response to these targets differed quite dramatically based on the selected attribute and response time. Considerable evidence indicates that activity in temporal regions comprising the ventral visual stream relates to semantic processing (Chan et al., 2004; Marinkovic, 2004; Scott, Leff, & Wise, 2003; Mangels et al., 2001; Price, 1998; Nobre et al., 1994; Demonet et al., 1992). Our results support the premise that attentional control can influence activity in task-relevant pathways at relatively early stages of processing, consistent with previous data indicating that processing of nonspatial features of stimuli can influence ERPs starting at approximately 200 msec (Hillyard & Anllo-Vento, 1998).

### **Relationship between Pre- and Poststimulus Activity on Word Trials**

Our results indicate that activity at right midfrontal electrodes during the preparatory period is related to activity at left inferior temporal electrodes after target

presentation when subjects attend to word meaning. Specifically, subjects who exhibited a greater change in amplitude between fast and slow word trials at right frontal regions also showed a greater change in amplitude of the ITN between fast and slow word trials. This suggests that preparatory activity at right frontal regions may prime the responsiveness of IT neurons that process semantic information, resulting in a potentiation of the IT response when target stimuli are actually presented. More importantly, we did not find a correlation between amplitude of prestimulus right frontal and P1 or N1 difference waves for either word or position trials. Although null effects are difficult to interpret, this lack of correlation suggests that the preparatory activity found at these frontal electrodes is not merely reflecting an increase in general vigilance or anticipatory attention, as it would be expected that greater vigilance during the preparatory period would be related to increased spatial orienting as indexed by the amplitude of the P1 and N1.

We also did not find a relationship between prestimulus central-parietal activity and poststimulus waveforms, in accord with previous suggestions that the parietal and prefrontal cortex play different roles in attentional processes (Brass & von Cramon, 2004; Sohn et al., 2000). A tentative suggestion is that regions of parietal cortex are involved in more general anticipatory or orienting mechanisms during the prestimulus period and not directly related to biasing of posterior processing regions. This would be consistent with results obtained by Sohn et al. (2000), who found that activity in posterior parietal cortex is related to general preparatory processes, whereas activity in the right prefrontal cortex is involved in specific task preparation. However, a relationship between prestimulus central-parietal activity and the P1/N1 waveforms might be expected if such a distinction existed, an effect that was not found in our study. Clearly, additional investigation into the differential contributions of frontal and parietal regions to attentional control is needed to further address this issue.

### **Conclusion**

In conclusion, we have obtained results suggesting that biasing of semantic processing regions (sites of attentional control) by the prefrontal cortex (source of attentional control) occurs in response to preparatory cues to attend to word meaning in a spatial Stroop task. More importantly, this preparatory activity is related to behavioral performance in that greater activity in frontal-parietal networks corresponds to faster RT in response to conflict stimuli. The cued Stroop is a useful paradigm to use in the study of preparatory attentional control, as advance preparation may be of particular value when needing to overcome cognitive conflict engendered by Stroop stimuli. Our spatial Stroop task enabled the investigation of activity at the sites of

semantic processing related to the less automatic task of responding according to word meaning achieved with ERPs. The excellent temporal resolution of this approach provides insight into the timing of verbal processing as reflected in the ITN. The effects of RT and cue type on the ITN were seen as early as 200 msec post-stimulus, indicating that attention impacts activity in task-relevant processing regions relatively early, consistent with the view that Stroop interference is related in part to conflict between stimulus representations (De Houwer, 2003; Zhang & Kornblum, 1998). As we did not find increased activity at the sites of attentional control during the preparatory period—a result that is in contrast with those obtained in some fMRI studies of selective attention and feature biasing—it would be useful to define specific task characteristics and methodologies that might facilitate detection of preparatory signals. Furthermore, our results suggesting a distinction between general versus feature-specific preparatory processing in the parietal and frontal cortex, respectively, are intriguing and require additional research to be fully understood.

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### Note

1. Previous trial cue type was also used as a factor for an initial phase of analysis due to concerns that differences in prefrontal activity could be driven by whether subjects had to switch cues or not (Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000). Although the percentages of fast and slow trials that came from switch trials were quite similar, there were slightly more trials that were slow and switch (54%) than fast and switch (47%), as might be expected. However, this factor did not interact with any of the critical effects described here. Thus, to simplify data presentation, all further analyses are presented without previous cue as a factor (see also West, 2003; MacDonald et al., 2000).

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