An ERP study of the temporal course of the Stroop color-word interference effect ☆

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Received 12 November 1998; received in revised form 23 June 1999; accepted 22 July 1999

Abstract

The electrophysiological correlates of the Stroop color-word interference effect were studied in eight healthy subjects using high-density Event-Related Potentials (ERPs). Three response modalities were compared: Overt Verbal, Covert Verbal, and Manual. Both Overt Verbal and Manual versions of the Stroop yielded robust Stroop color-word interference as indexed by longer RT for incongruent than congruent color words. The Incongruent vs Congruent ERP difference wave presented two effects. A first effect was a medial dorsal negativity between 350–500 ms post-stimulus (peak at 410 ms). This effect had a significantly different scalp distribution in the Verbal and Manual Stroop versions, with an anterior–medial focus for overt or covert speech, and a broader medial–dorsal distribution for the manual task. Dipole source analysis suggested two independent generators in anterior cingulate cortex. Later on in time, a prolonged positivity developed between 500–800 ms post-stimulus over left superior temporo-parietal scalp. This effect was present for all the three response modalities. A possible interpretation of these results is that Stroop color-word interference first activates anterior cingulate cortex (350–500 ms post-stimulus), followed by activation of the left temporo-parietal cortex, possibly related to the need of additional processing of word meaning. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Stroop color interference task is among the most extensively studied paradigms in cognitive psychology. The classical behavioral effect consists of a lengthening in reaction time to color naming when the word meaning and the presentation do not match (i.e., they are "incongruent") relative to when they correspond (i.e., they are "congruent") [31]. At a psychological level, the Stroop effect has been best explained in terms of response competition. Longer reaction time

and greater interference is present when the irrelevant attribute of the stimulus (the word meaning) is analyzed faster (i.e. is more automatic) than the relevant attribute (color), and the unwanted response is therefore available first ("race" model) [21].

Lesion correlation data in stroke patients [28,35], and neuroimaging studies in healthy volunteers [6,8,11,13,20,22,33] have greatly improved our understanding of regions in the brain mediating the attentional demands involved in the Stroop color word interference. More specifically, the anterior cingulate cortex appears to be heavily involved, although other areas have been less consistently reported, such as inferior frontal cortex, parietal cortex, posterior cingulate and motor and premotor regions. The original Positron Emission Tomography (PET) findings generally supported the construct of an anterior attentional system involved in target detection and response selection, especially when confronted with conflicting stimulus or response biases [24,25].

Considerable interest in the Stroop Task derives from its growing utility as a diagnostic and research tool to probe executive function in frontal lobe injury [28,35] and psychiatric disease. In depression and schizophrenia, Stroop performance is generally impaired. PET abnormalities in the anterior cingulate have been described both at rest and during attentional performance [5,9,12,14,17,18]. In depression, abnormal resting state hypometabolism and hypoperfusion have been reported in all portions of the anterior cingulate, including the ventral subgenual [12,18], the rostral [17], and the dorsal [5,18] partitions. The dorsal anterior cingulate abnormality in both depression and schizophrenia corresponds to the region implicated in selective attention by previous PET studies in normals [24,25].

In spite of the well-replicated finding of anterior cingulate involvement in the Stroop color interference task delineated by cognitive neuroimaging studies using PET [6,8,11,13,22,33] and recently functional Magnetic Resonance Imaging (fMRI) [20], several key aspects of the neuropsychology of the Stroop effect are still unknown. The first concerns the temporal course of the activations in the network of brain regions involved in the execution of the Stroop task. PET is limited by long integration time (40–120 s), and fMRI is limited by the long duration of the hemodynamic response (several seconds), although Event-Related fMRI appear as a promising technique to improve its temporal resolution [7,27]. Event-Related Potentials (ERPs) possess exquisite temporal resolution (ms level), but only coarse spatial resolution — improved by the use of high-density electrode arrays [34]. ERPs have the potential to identify the timing, order of activation, and dynamic orchestration of brain regions during the unfolding of the Stroop task. Secondly, because of the limited temporal resolution, PET and conventional fMRI only allow block paradigm design. This has been the case for all the available neuroimaging studies of the Stroop effect, whereas most typically blocks of "incongruent" color words have been contrasted to blocks of "congruent" color words [6,8,11,13,20,22,33]. It can be argued that under these conditions the Stroop Task sums up to a rather different task. First, the elements of switching and unpredictability are absent. Second, the "incongruent" blocks appear intuitively to require a different attentional set, a higher level of sustained attention and arousal, and possibly a different processing strategy altogether (effortful rather than automatic). In addition, in "congruent" blocks the word color may become irrelevant to the task, since the more automatic processing of the word meaning alone is sufficient to correctly perform the task. In contrast to PET and MRI, ERPs capitalize on selective averaging of different stimulus types within the same experimental block (i.e., "congruent" words and "incongruent" words), allowing mixed-trials analysis of the Stroop task in its unadulterated and classical form. Finally, alternative response modalities during the Stroop task that are less problematic in terms of motion artifacts in fMRI, such as manual and covert vocal, have not been much explored before in any imaging modality [2,15,26].

Three published ERP studies have addressed the Stroop effect. The first used only two color words, employed manual responses, and reported exclusively early color selection effects [26]. The second is a recent study using a covert version of the original Stroop task [2]. The third used three color words and employed only manual responses [15]. All of these studies only employed several electrodes, in the midline only. The paucity of studies employing the Stroop paradigm may be partly explained by the concern with contamination of the cognitive effects with overt speech artifacts and other motion artifacts frequently observed during speech [30,36].

The aim of the present study was to investigate the temporal course of known brain activations during the conventional, mixed-trial Stroop color-word paradigm using high-density (64 channel) ERP recordings. An additional goal of the study was to directly contrast within the same subjects and sessions the conventional version of the Stroop task (Overt Speech) with two alternative response modalities: a covert color naming condition, and a four-choice manual version of the task. This approach allowed us to examine the dependence of the Stroop effect brain activations on the particular response modality employed, as well as being of general interest for future studies of the Stroop effect using brain activity measures that are highly vulnerable to motion artifacts, such as ERPs and fMRI.

2. Methods

2.1. Subjects

Eight healthy volunteers (right-handed, age 27.6 ± 6.8 years, three men, five women) participated in the study. Subjects had no history of current or past neurological or psychiatric illness, vision was normal or corrected-to-normal. Informed consent was obtained from all subjects according to the norms of the University of Texas Health Science Center Institutional Review Board.

2.2. Stimuli and task

Subjects were seated in a reclining chair facing a monitor placed at 40 cm from their eyes. They were presented with the words "red", "green", "blue" or

"yellow" just above central fixation presented on a dark grey screen. Stimulus duration was 150 ms, stimulus size was 1.8–3.6° (horizontal) × 0.7° (vertical), and interstimulus interval varied randomly between 1700–2200 ms. In the Stroop conditions, half of the words were randomly presented in the congruent color (e.g., the word "red" in red ink), and half in any of the other three (incongruent) colors. In the Non-color conditions, all words were in light grey ink. There was a total of eight conditions. In the *Stroop-Verbal Overt* condition, subjects said aloud the presentation color of the word, and vocal onset time was recorded through a microphone placed in front of the subject. In the *Stroop-Verbal Covert* condition, subjects were instructed to say the color of the word silently in their mind, without moving their lips, tongue and jaw at all. In the *Stroop-Manual4* condition, subjects responded to the color of the word by pressing one of four buttons of a corresponding color on a gamepad, two buttons in each hand. Reaction time and errors were concomitantly recorded. There were five additional control tasks. In the *Stroop-Passive* blocks, color words were passively flashed on the screen. In the *Stroop-Manual1* condition color words appeared on the screen, and subjects responded to the appearance of any word by pressing the same (blue) key with the right hand (manual simple reaction time). In the *Stroop-Vocal1* CONDITION color words appeared on the screen, and subjects responded by saying aloud "baagaa" (vocal simple reaction time). In the NonColor conditions, the same words were presented in white ink. In the *NonColor-Manual4* blocks, subjects responded to each word meaning (red, green, blue, yellow) with one of four buttons as in the *Stroop-Manual4* condition. In the *NonColor-Verbal Covert* condition subjects had to covertly read the word.

There was a total of 36 runs, of which eight each were Stroop-Covert and Stroop-Manual4; two were Stroop-Overt, and four each of the remaining tasks. Each run had a total of 72 stimuli (36 congruent and 36 incongruent color words for the Stroop blocks) and lasted about 2.5 min. There were 144 stimuli in the Stroop-Overt blocks (72 each were congruent vs incongruent color-words), and 576 stimuli in all other tasks. The Stroop-Covert and Stroop-Manual4 had 288 stimuli each for congruent and incongruent color-words.

Before starting the experimental session, subjects had a short practice on the Stroop-Overt task, and a block of practice on the NonColor-Manual4 task in order to learn the 4-way response configuration. Reaction time from stimulus onset to a button press or the onset of a vocal response were recorded to the nearest ms.

Repeated-measures Analyses of Variance (ANOVAs) were employed for the following behavioral parameters: Mean reaction time (RT) to all conditions for which response latency was recorded (Hits, 200–1500 ms), and rate of Errors for the congruent vs incongruent color words in the manual version. Within factors were Type of Task (Manual4 vs Verbal4) and Type of Stimulus (Congruent vs Incongruent).

2.3. EEG recording

Brain electrical activity was continuously recorded using a customized 64 channel cap (Electrocap Inc[®], Eaton, OH) including four eye movement electrodes (two at the external canthi and two infraorbital) and a left mastoid electrode, all referenced to the right mastoid (bandpass = 0.01–100 Hz, gain = 10^4, sampling rate = 400 Hz, impedances < 5 kΩ). Eye movement artifacts (blinks and eye movements) were rejected off-line. Blink artifacts were rejected in all tasks based on the voltage amplitude at frontal supraorbital sites, since speech-related activity in the overt speech tasks was accompanied by high amplitude potentials at the inferior orbital sites which did not invert over the frontal scalp.

ERPs to the onset of the color words (500 ms pre-stimulus baseline and 2000 ms post-stimulus) were selectively averaged for each subject and for each of the following conditions: for the Stroop tasks (Overt-Verbal, Covert-Verbal and Manual4), independent averages were obtained for congruent and incongruent color-words (correct hits only were included in the Overt-Verbal and Manual4 task); for all other conditions (Stroop-Passive, Stroop-Manual1, Stroop-Verbal1, NonColor-Manual4, NonColor-Covert), all stimuli were averaged together. ERP processing included algebraic re-referencing to average reference [34], and smoothing by application of a seven-point running average. ERP subject averages for each condition were then grand-averaged across the eight subjects. ERP amplitudes were aligned to a 200 ms pre-stimulus baseline period. The main ERP effects of interest concerned the contrasts between color-congruent and color-incongruent words in the Stroop-Verbal Overt, Stroop-Verbal Covert, and Stroop-Manual4 conditions. Inspection of the grand-average waveforms for these contrasts (Fig. 1), as well as inspection of sequential topographical maps of the Incongruent minus Congruent ERP difference waves (Fig. 2) indicated that there were two major effects of color-word interference: an early effect (350–500 ms), and a late effect (500–800 ms) (see Figs. 1 and 2).

The early effect was explored in 50 ms time windows from 350 to 500 ms (see Table 2). We tested the apriori hypothesis that medial dorsal scalp regions above the cingulate gyrus would show Stroop-related changes. Four midline sites along the anterior–posterior axis (Fcz, Cz, Pzs, Pzi) and four adjacent parasagittal lateral sites were selected. For each time

window (350–400, 400–450, 450–500 ms) and each response modality (Covert, Overt and Manual), repeated-measures ANOVAs were conducted, with factor being Trial Type (Congruent vs Incongruent), Anterior–Posterior location, and Laterality (left, midline, right). A further analysis was conducted to statistically explore differences in scalp distribution between response modalities at the peak of the effect (400–450 ms). This analysis was carried out on the Incongruent minus Congruent difference waves, after the voltage data were normalized using the square root of the sum of squares method [19]. Response type was included as a factor.

The late effect was explored in 100 ms time windows from 500 to 800 ms (Table 2). In order to explore the timing of such effect over frontal and left posterior areas, a repeated-measures ANOVA was conducted in each time window (500–600, 600–700, 700–800 ms) within each response modality, using three electrode sites on each hemisphere: an anterior frontal site (F3a-F4a; F3 and F4, anterior), a central site (C5a-C6a; C5 and C6, anterior), and a parietal site (P3i-P4i; P3 and P4, inferior). For all analyses, P-value was set at 0.05, corrected for deviations from sphericity (Greenhouse–Geisser epsilon method).

ERP source analysis was also performed on the Incongruent vs Congruent difference wave for the Covert and Manual Stroop tasks, using the BESA software (brain electrical source analysis) program [29]. This program places simulated dipoles in a three-shell spherical head model, and iteratively adjusts their locations and orientations to try to achieve the best fit between observed scalp potentials and the distributions that the model dipoles would produce.

3. Results

3.1. Task performance

In the mean Reaction Time analysis (Table 1), a very robust Stroop color-word interference effect was obtained both in the Vocal version of the task, $F(1,7) = 104.8$, $P < 0.0001$, mean effect size = 85 ms; and in the manual version of the task (Manual4), $F(1,7) = 47.8$, $P < 0.0001$, mean effect size = 110 ms. For both choice and simple RT versions of the task, vocal and manual RTs were not statistically different. Similarly, RTs to the congruent color-words (Manual4) were the same as RTs to the words in the Non-Color4 condition, $F(1,7) = 0.05$, n.s. For the accuracy data, restricted to the manual version of the Stroop task, percent errors for incongruent color-words, congruent color words, and non-color words were entered in a one-way ANOVA. Stimulus type was significant, $F(2,14) = 5.1$, $P = 0.02$. Simple mean effects revealed

significantly more errors for incongruent than congruent and control color words, $F = 8.6$, $P = 0.01$, and $F = 6.6$, $P = 0.022$, respectively, and no difference for congruent color words vs control non-color words, $F = 0.13$, $P = 0.73$, ns.

3.2. Event-related potentials

Fig. 1 shows the grand average ERP waveforms for FCz, Cz, Pzs (Pz, superior), and Pzi (Pz, inferior) for the Stroop color words for the congruent and the incongruent words for the Overt Verbal version of the Task (left), the Covert Verbal task (center), and the Manual version of the task (right). Note that the ERPs for Incongruent and Congruent color words diverge between 350–500 ms over scalp, with the Incongruent color word presenting a negative wave (peak at 410 ms) that is reduced in the ERP to the congruent color word. Second, in the Covert and Overt versions of the task the effect is centered over medial anterior scalp, while in the Manual Stroop task there is a more posterior and broader scalp distribution including anterior as well as central and posterior dorsal scalp (Fig. 1, right), and appearing slightly left-sided.

Fig. 3 shows the later Incongruent vs Congruent difference between 500 and 800 ms (peaking with a maximum 600–700 ms), which center was on the left posterior superior (temporo-parietal) scalp region and inverting over the anterior frontal region, that appears to be due to a more protracted late positive complex (LPC) for Incongruent than Congruent and Control color words for all response modalities (Fig. 2).

3.3. Early medial color interference (Stroop) effect (350–500 ms)

Table 2, top shows the results of the ANOVAs for each of the time windows examined and each response modality. The strongest effects were in the 400–450 ms window. For the Covert and Overt versions of the task, there were significant Trial Type × Site interactions. Specific comparisons analyzing the source of these interactions revealed that in the Overt task, there were significant Trial Type differences at frontocentral ($F = 33.8$, $P = 0.002$) and central sites ($F = 23.7$, $P = 0.005$) but not at posterior sites (simple mean effects). There was also a significant interaction with laterality, due to a significant effect on the left at FC sites, but not on the right (see Fig. 1). Similarly, for the Covert task Stroop effects were present over frontocentral ($F = 47.7$, $P = 0.0004$) and central scalp ($F = 20.6$, $P = 0.005$), but not over posterior scalp, with no laterality effects. In contrast, in the Manual task, there were strongly significant main effects of Trial type, but no hint of a significant interaction with site, due to a
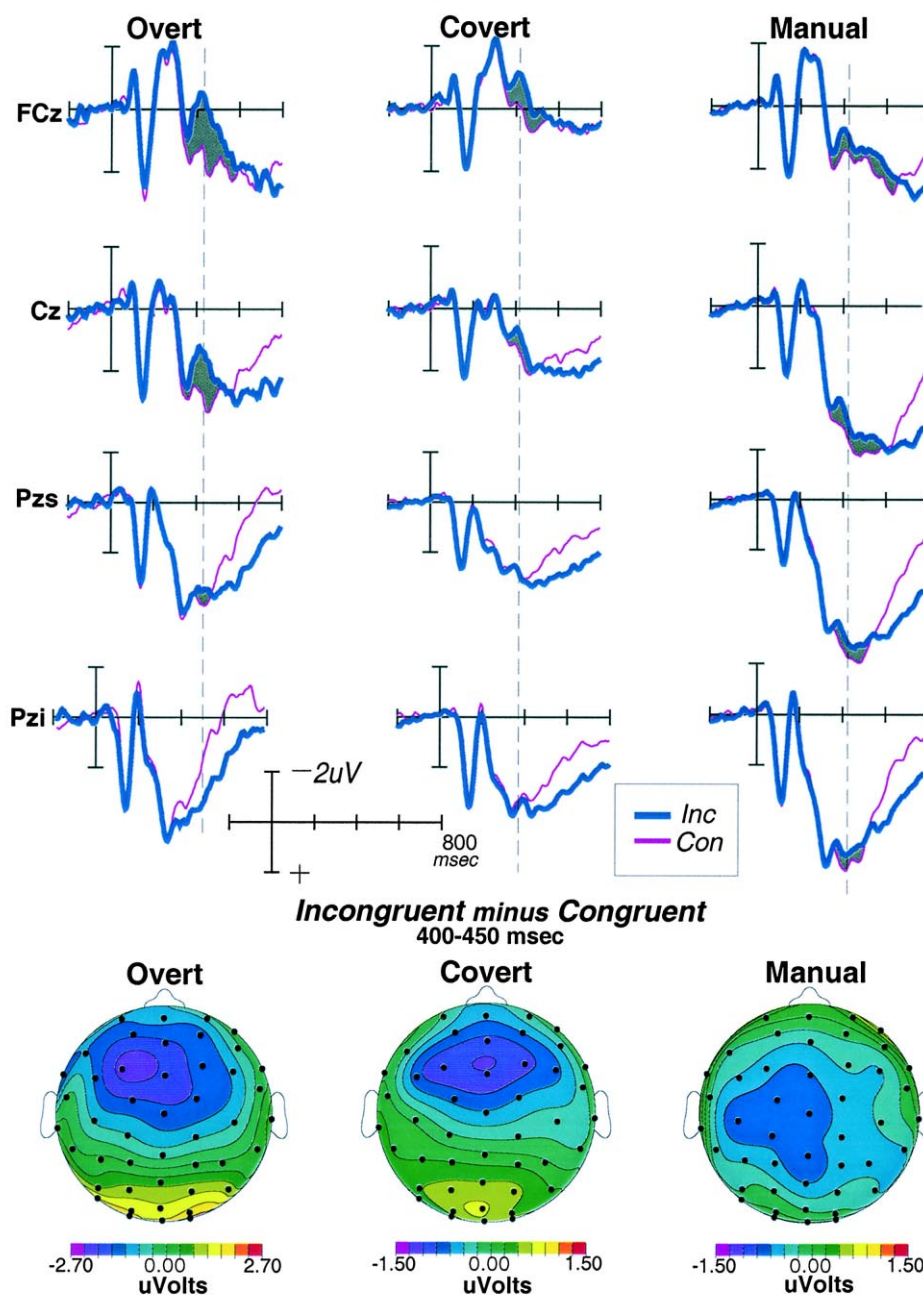
Fig. 1. Top: Grand-average ERPs at FCz, Cz, Pzs and Pzi for Congruent color words (purple line) and Incongruent color words (blue line) Left: Overt verbal task. Center: Covert verbal task. Right: Manual task. Vertical dashed line indicates peak of early frontal effect across the three versions of the task.

Bottom: Topographical maps of the voltage amplitudes for the Incongruent vs Congruent color word difference wave in the 400–450 ms window. Left: Overt verbal task. Center: Covert verbal task. Right: Manual task. Note the change in scalp topography between verbal versions of the task (anterior medial) and the manual version of the task (broad dorsal).

broader distribution of the Incongruent vs Congruent negative difference extending over central and parietal sites as well (Table 2, top right).

The hypothesis of a scalp distribution difference of the early Stroop effects between response modalities was confirmed by the results of the analysis on the Incongruent minus Congruent difference waves, after amplitude normalization [19]. As predicted, there was a significant Response Modality × Site interaction, $F(6,42) = 6.0$, $P < 0.008$. As expected, this interaction was due to a significant difference between Covert/Overt Tasks and the Manual Task at the two posterior scalp locations ($P < 0.01$), and no difference over anterior and central sites (Fig. 2, left).
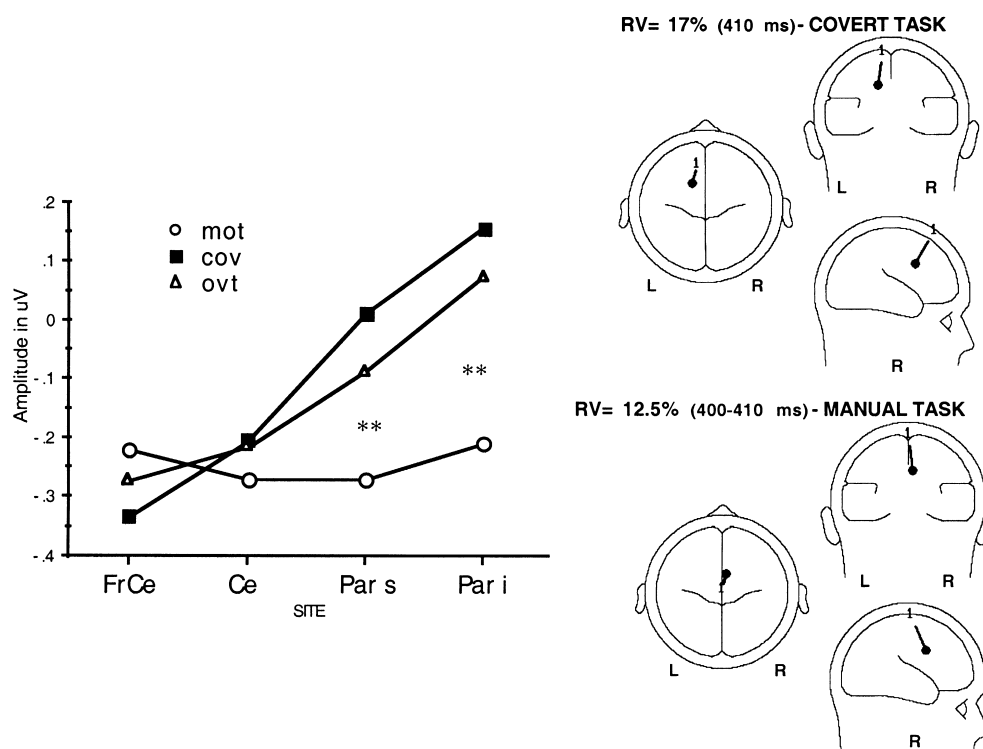
Fig. 2. Left: Mean Amplitudes of the Incongruent minus Congruent difference wave (400–450 ms) for each combination of scalp topography and type of task. The early negativity is similar over frontocentral (FrCe) and Central (Ce) scalp, but significantly different over superior and inferior parietal scalp (Par s, Par I) for the speech and manual versions of the task.

Right: BESA source dipole solutions for the early Stroop interference effect in the covert task (top) and manual task (bottom). RV = Residual Variance. For both tasks, a dipole was placed in R anterior Cingulate [22]. z was kept fixed (to constrain a solution in Anterior Cingulate), while x, y and the orientation were free to vary.

To gain further insight into topographic differences between the Stroop effects for the different response modalities, as well as into possible sources for these effects, we applied dipole source modelling to the early medial effect using the BESA program [29]. Our first approach to this modelling was to seed BESA with the stereotactic coordinates [32] of the anterior cingulate effect in Pardo et al.'s PET Stroop study ($x = 8$, $y = 15$, $z = 32$ mm) [22], with the orientation only left to vary. At the peak of the activity (410 ms), this yielded a solution with a residual variance (RV) of 20.3% for the Covert Task, and 14.7% for the Manual Task (not

shown). We then proceeded with the following logic: Since we were interested in localizing possible generators within dorsal cingulate cortex, we let x, y, and orientation of the dipole vary, while keeping the same z. This yielded improved single dipole solutions, to an RV = 17% for the Covert task and an RV = 12.5% for the Manual task (see Fig. 2, right). The stereotactic coordinates [32] were $x = -11$, $y = 6$, $z = 32$ mm for Covert, with the Manual effect dipole estimate being more posterior ($x = 7$, $y = -2$, $z = 32$). Thus, assuming our hypothesis that a major source of this activity was arising from anterior cingulate cortex, these modelling

Table 1

Summary of performance data. Top row: Group mean reaction time and standard deviation for the different conditions of the study. Bottom row: Group mean percent errors and standard deviation for the different conditions of the study

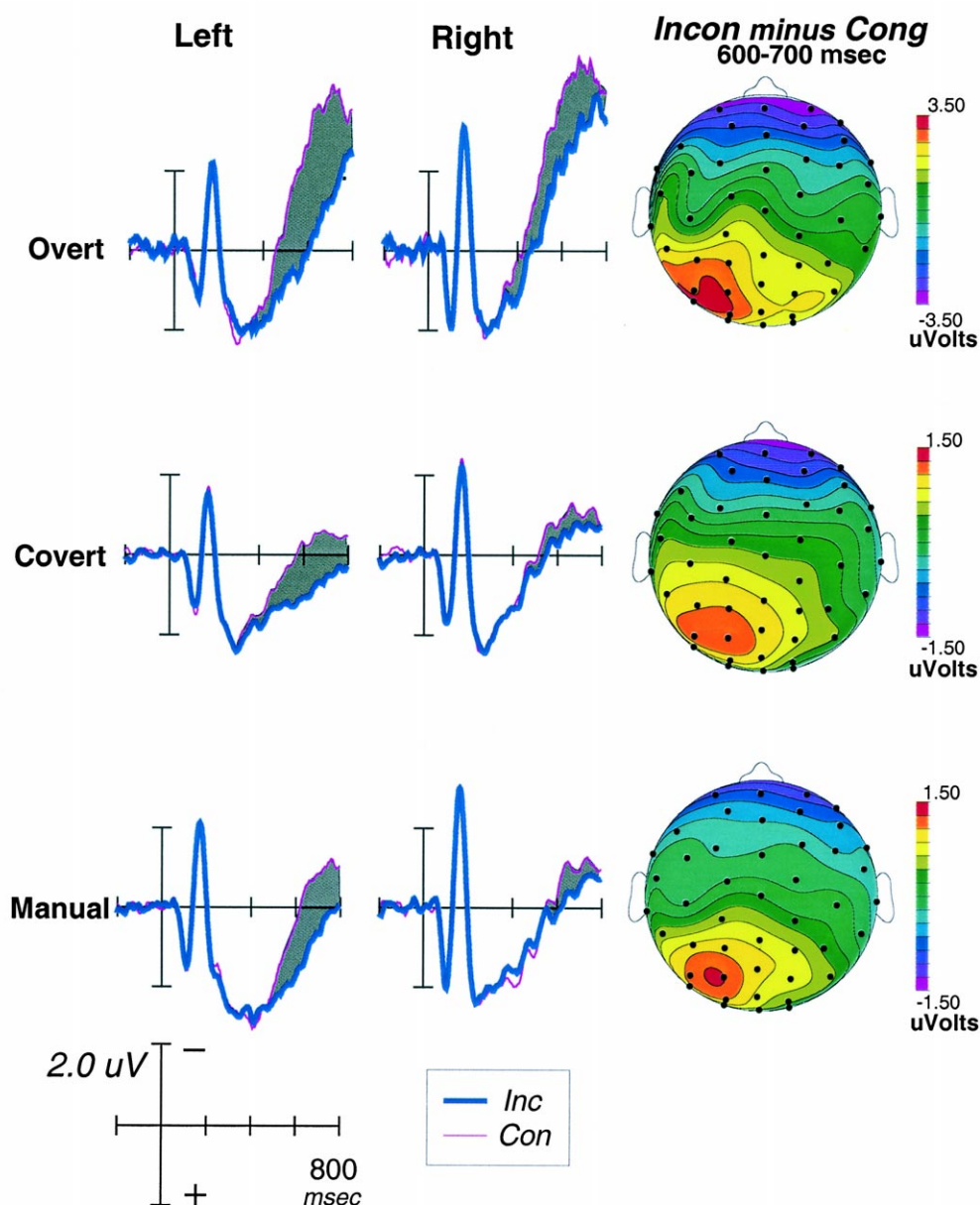| Task	Non-color Man4 (Contr)	Stroop Man4 (Cong)	Stroop Man4 (Inc)	Stroop Vocal4 (Cong)	Stroop Vocal4 (Inc)	Stroop Man1	Stroop Vocal1
Mean RT	601 (81)	598 (88)	708 (117)	627 (110)	712 (103)	284 (39)	332 (82)
Errors	3.1 (2.0)	2.2 (1.2)	9.2 (9.2)				

Fig. 3. Grand-average ERPs at P3i and P4i for Congruent color words (purple line) and Incongruent color words (blue line). Top: Overt vocal task. Center: Covert vocal task. Bottom: Manual task. On the right are topographical maps of the voltage amplitudes for the Incongruent vs Congruent color word difference wave at in the 600–700 ms window. Note the similar left-sided scalp distribution in the three versions of the task.

results suggested somewhat different but nearby generators in this region for the Stroop effect in the Speech and the Manual versions of this task. This result is consistent with the significant differential scalp distribution of these effects reported above (Fig. 2).

3.4. Late color interference (Stroop) effect (500–800 ms)

Table 2, bottom, shows the results of the ANOVAs for each of the time windows examined and each re-

sponse modality. The strongest effects were in the 600–700 ms window. For all response modalities, there was no main effect of Trial Type, but significant Trial Type × Site interactions. For all tasks, effects were significant over frontal scalp (Overt: $P = 0.001$, Covert: $P = 0.01$, Manual: $P = 0.007$) and parietal scalp (Overt: $P = 0.004$; Covert: $P = 0.03$; Manual: $P = 0.02$). For all response modalities, there was a significant Trial Type × Hemisphere interaction, due to Incongruent words being more positive over the left hemisphere, and no difference for Congruent words (Fig. 3). The effects

Table 2
Top: Summary of results for the ANOVAs on the early Stroop effect (top) for the 350–400, 400–450, and 450–500 ms time windows. Bottom: Summary of results for the ANOVAs on the late Stroop effect for the 500–600, 600–700, and 700–800 ms time windows[a]

Task	Overt				Covert				Manual			
	Trial		Trial × Site		Trial		Trial × Site		Trial		Trial × Site	
Time (ms)	F	P	F	P	F	P	F	P	F	P	F	P
Early effect												
350–400	1.6	ns	4.9	0.06~	1.7	ns	5.8	0.04*	5.8	0.05*	1.6	ns
400–450	4.4	0.08~	8.7	0.02*	2.4	ns	15.6	0.002***	28.6	0.001****	0.1	ns
450–500	2.3	ns	11.8	0.008**	0.1	ns	8.1	0.02*	3.1	ns	1.2	ns

Task	Overt						Covert						Manual					
	Trial		Trial × Site		Trial × Hem		Trial		Trial × Site		Trial × Hem		Trial		Trial × Site		Trial × Hem	
Time (ms)	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P
Late effect																		
500–600	1.3	ns	21.6	0.002***	2.3	ns	0.0	ns	6.2	0.04*	6.4	0.04*	0.1	ns	2	ns	8.7	0.02*
600–700	0.5	ns	29.6	0.001****	4.6	0.07~	1.0	ns	12.0	0.009**	9.2	0.02*	1.3	ns	15.7	0.004***	5.1	0.06~
700–800	0.0	ns	7.0	0.03*	4.9	0.06~	1.0	ns	10.4	0.002***	3.6	ns	1.2	ns	9.7	0.02*	7.7	0.03*

[a] * = < .05; ** = < .01; *** = < .005; **** = < .001; ~ = < .10.

over frontal and left parietal scalp had identical timing features in all modalities. Modelling of the dipole sources of the late Stroop effect was not carried out, because it was unlikely to have been produced by anterior cingulate activation, and because we had no apriori hypothesis on the location of the generator, since this late posterior left-sided effect does not appear to have a clear counterpart in previous PET studies of the Stroop effect.

4. Discussion

In the present study, robust behavioral and electrophysiological effects of color-word interference were obtained across various versions (overt, covert, manual) of a mixed-trial Stroop task. Strong behavioral effects were obtained both in the standard vocal version of the task and in a manual choice-RT version of the task. Electrophysiological effects were obtained in all three Stroop conditions, including the covert vocal conditions for which no behavior was available. Across the three tasks, processing of each attention-demanding incongruent color word relative to the more automatic processing of the congruent color word resulted in a biphasic activation involving first medial dorsal scalp, and then left temporo-parietal and anterior frontal scalp.

These data provide new information on the time

course of the Stroop effect. In line with previous PET findings in the Stroop paradigm, we interpret the early negativity as originating in dorsal anterior cingulate cortex and relating to the need of suppressing or overriding the processing of the incongruent word meaning. We interpret the late effect as later re-activation of left-sided regions involved in retrieval of the meaning of the incongruent color word.

4.1. Early anterior color interference effect (350–500 ms)

This consisted in a greater negativity of the Incongruent minus Congruent color word difference peaking at 410 ms. The effect in the present study had a distinct scalp topography for the speech and manual versions of the task (see Fig. 1), with a more focal anterior medial distribution in the first, and a significantly different, and more diffused, mid-dorsal distribution for the second. Dipole source modelling suggested two independent sources in anterior cingulate cortex for speech and manual modalities (see Fig. 2, right). The anteromedial region activated in the speech version of the task is reasonably close to the dorsal anterior cingulate activations reported in PET studies of the Stroop effect [i.e., 6,22]. Our data indicate that a Covert Stroop task involves the same activations in anterior frontal cortex as the classical version of the task, for which a behavioral effect can

be concomitantly demonstrated. Therefore, the Covert version can be employed in fMRI studies provided perhaps that behavior is recorded in the same subjects and sessions shortly before or after to insure monitoring of cognitive performance in an overt version of the task.

In the present manual 4-choice version of the Stroop task, robust RT interference effects were obtained, but a significantly different scalp distribution was observed, with a more diffused dorsal negative difference spanning from anterior to posterior sites. Dipole modelling suggested a more posterior source in anterior cingulate cortex. (Figs. 1 and 3). Our data indicate that manual Stroop implicates different subregion(s) of the anterior cingulate than the classical vocal version of the Task. It has been hypothesized that a crucial role of the AC region is response selection [24,25]. It is possible that different AC subregions may be involved in the selection of competing responses using different effectors. This interpretation is supported by PET evidence of non-overlap of AC activations using hand, speech and saccadic responses [23] and by recent evidence that AC lesion (ACA aneurysm rapture) produces impaired manual Stroop but not Verbal Stroop [35]. In addition, a recent high density ERP study suggested independent sources in the anterior cingulate associated with error detection and target monitoring [3].

Our results have important implications for future neuroimaging studies of the Stroop task. An Overt version of the Stroop task is considered to be difficult to employ with either ERPs or fMRI, due to motion artifacts associated with overt speech. In this study, we found that Stroop-related responses in the Overt task were mostly spatially and temporally separable from speech artifacts (most likely of muscular origin: tongue, lips and jaw movements and contraction of the masticatory muscles) which tended to produce large amplitude potentials with negative polarity over the inferior orbital region, and positive polarity over inferior occipital scalp areas bilaterally (at or below the Inion). The anterior Stroop incongruency effect was present with the same spatio-temporal features in the Covert version of the task, in which no overt speech was produced and the speech artifacts were absent (see in Fig. 1). These results indicate that ERPs can be recorded for cognitive tasks involving overt speech, when the cognitive effects of interest do not overlap in time or space with such speech artifacts and special care is taken to selectively remove eye-movement activity [30,36].

Finally, it is important to compare the early interference effect with other published ERP findings with similar latency and scalp distribution. The Stroop interference effect is in the time range of the N400, an ERP difference wave observed when a semantic context built by a sentence or a previous word is violated (e.g., I eat my toast with "butter" vs I eat my toast with "socks"). The only published ERP study using the original Stroop task (covert version) reported an incongruent color interference effect peaking at 400 ms, as in the present study [26]. That effect had a similar broad dorsal distribution, with centro-parietal maximum as the traditional N400 [10,16], and was in fact interpreted as an N400 [26]. However that study employed a few electrodes, only in the midline. A more anterior scalp distribution (midline frontal) of a N4-like effect has been observed in studies in which nameable object meaning violated a previously established semantic context [4]. Importantly, an N400 interpretation appears unlikely in view of the different scalp distribution of the interference effect for speech and manual responses.

4.2. Late left posterior color interference effect (500–800 ms)

A secondary finding of this study was the identification of a more extended late positive complex (LPC) in the incongruent relative to the congruent color word peaking 600–700 ms post-stimulus onset and centered over left posterior superior scalp, inverting polarity over anterior frontal scalp. Such effect replicated quite well in the three versions of the task (see Fig. 2, right). This difference is highly suggestive of a recursive process in which re-entrant activation of posterior word processing regions takes place upon signalling of color incongruence by anterior regions, possibly the anterior cingulate area. We were not able to temporally separate the left posterior positivity from an equally strong anterior frontal negativity (Fig. 3, Table 2), since they appeared to wax and wane together. Although we cannot rule out the independent contribution of anterior frontal generators shown to play a role in ERP studies of semantic processing of words [1,3,30,36], the combined frontal and posterior distribution is more suggestive of a major contribution from a left posterior generator. Similar topography inversions from dorsal scalp to ventral scalp regions have been reported for both the P300 and the N400 using the average reference (as used here) rather than a mastoid reference [1,34,]. A number of high-density ERP studies support the idea that the left-lateralized LPC effects may reflect semantic processing of the word meaning. In particular, a left-lateralized LPC effect with similar scalp distribution and timing was observed when the ERP covertly or overtly repeating a word was subtracted by the ERP covertly or overtly generating a verb related to a presented word [1,30,37]. Dipole modelling provided solutions interpreted as sources in the Wernicke's region [1,30].

5. Conclusion

The results reported here would not have been possible without the selective averaging capabilities provided by the ERP technique, allowing the extraction of the specific contribution of congruent and incongruent words within the same blocks of trials, and without the high temporal resolution provided by ERPs, indicating the exact temporal course and the highly dynamic nature of these effects.

This study clarifies the timing of activations during the Stroop color-word interference effect. An early negative interference effect peaks at 410 ms, with different scalp topography for speech and manual versions of the task, and distinct anterior source generators, possibly in the Anterior Cingulate region. This effect is followed by a protracted late positive complex for incongruent relative to congruent words between 500–800 ms, centered over left posterior superior (temporoparietal) cortex and anterior frontal areas, possibly reflecting activation of word meaning regions.

Acknowledgements

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