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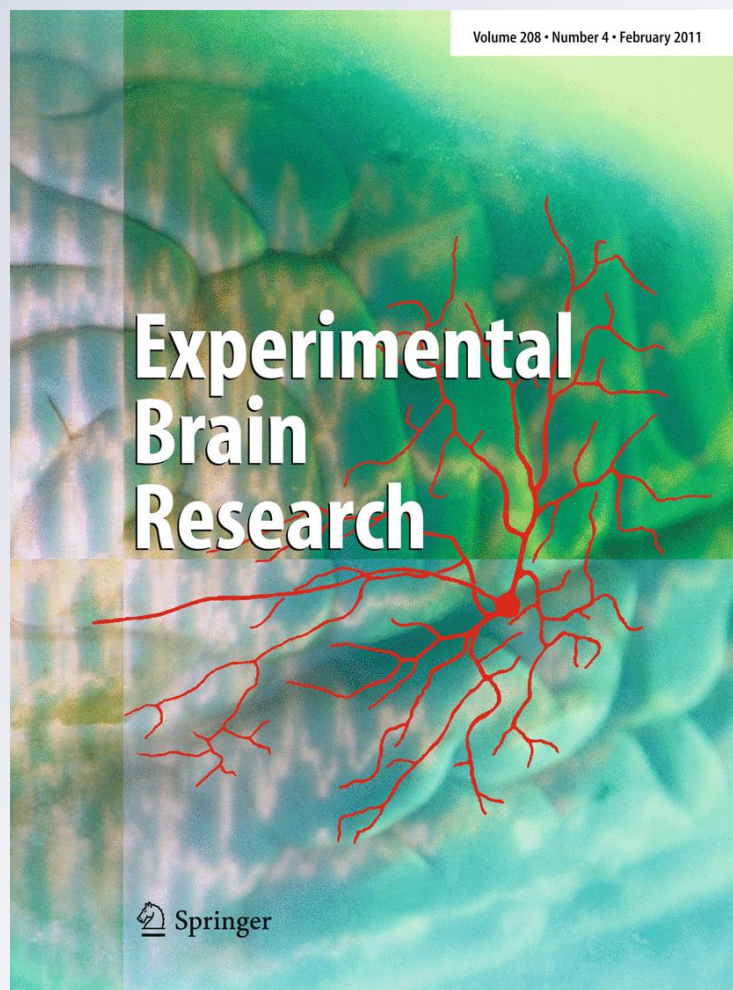Springer

RESEARCH ARTICLE

Stroop matching task: role of feature selection and temporal modulation

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Abstract We conducted an event-related potential (ERP) study to investigate the electrocortical dynamics of attentional feature-based processing in the Stroop matching task. Participants in the study ($n = 37$) compared the ink color of a colored word with the meaning of a color–word in white ink. The two task stimuli were presented simultaneously or with SOAs (Stimulus Onset Asynchrony) of 400 and 1,200 ms. The Stroop matching effect was maximal during SOA-0, was reduced at SOA-400, and was inverted at SOA-1200. We focused the ERP analysis on the N1 component. Paralleling the behavioral results, the N1 amplitude was greater for congruent stimuli than incongruent stimuli during SOA-0. This difference was attenuated at SOA-400, and at SOA-1200, an inverse pattern was observed. The results provide evidence that early selection processing participated in the Stroop matching task phenomenon and also suggest that the temporal modulation of early attention is a function of task characteristics such as SOA.

Keywords Stroop · ERP · Feature attention · Matching task

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Introduction

Selecting relevant aspects of the visual scene when facing multiple, conflicting stimuli features is required for the complex visual environment in which we live. The Stroop effect describes the increased time to respond to a target feature in the presence of one or more incongruent but irrelevant features. In the traditional Stroop task (Stroop 1935), a pronounced delay occurs when a word such as BLUE appears in a different ink color (e.g., red), and participants are asked to name the color while ignoring the word. There are many variations of the original Stroop task. In this study, we focused on the so-called Stroop matching task, in which congruent or incongruent Stroop stimuli were presented with either a colored patch, a sequence of colored "X"s, or another color–word printed in neutral ink (Durgin 2003; Goldfarb and Henik 2006; Luo 1999; Mascolo and Hirtle 1990; Simon and Berbaum 1988;

Treisman and Fearnley 1969; Zysset et al. 2001). Volunteers compared the relevant features of both stimuli and indicated whether the stimuli matched or not.

The work of Treisman and Fearnley (1969) initiated the Stroop matching task discussion and contributed to some theoretical aspects related to Stroop-like interference. Treisman and Fearnley (1969) asked the participants to match the color or the word of the Stroop stimulus with a color–word in black or with a sequence of colored "X"s. The participants found that it was more difficult to perform between-feature matching (color–word or word–color comparisons) than within-feature matching (word–word or color–color comparison) when incongruent colored words were used. Such pattern of results, i.e., longer response times for incongruent Stroop stimuli than congruent Stroop stimuli (a congruency effect), especially for between-features comparisons, has been used by some to support a translational account of Stroop interference (Glaser and Glaser 1989; Virzi and Egeth 1985). The translational theory states that interference occurs when a response requires translation between the internal code of the relevant attribute to another code according to the response (e.g., during color–word or word–color comparisons). After the classic work of Treisman and Fearnley (1969), several studies have explored the Stroop matching task using different approaches. Typically, these studies also observed the congruency effect especially for between-feature comparisons (e.g., Luo 1999; Simon and Baker 1995; Sugg and McDonald 1994).

Some Stroop matching task studies have examined the congruency effect along a time-course, by varying the Stimulus Onset Asynchrony (SOA) between the two stimuli (Flowers 1975; Machado-Pinheiro et al. 2010; Sugg and McDonald 1994). In those studies, the congruency effect in between-feature comparisons was significantly reduced with increasing SOAs. A similar decrease in the congruency effect with relation to SOAs has been observed in other Stroop-like tasks, such as when using oral responses and presenting the distracter word (in a neutral ink) prior to the relevant ink and varying the SOA (e.g., Dyer 1971; Glaser and Glaser 1982). These findings suggest that the activation pattern, related to the Stroop effect network, is sensitive to the temporal relationship between stimuli. Furthermore, this temporal component of the Stroop effect has been recently observed in an event-related potential (ERP) study (Appelbaum et al. 2009), revealing the SOA manipulation as a useful tool to modulate Stroop-like interference ERP effects.

Based on behavioral Stroop matching tasks findings, it was postulated that semantics, more than response competition, played a larger role in Stroop-like interferences (Luo 1999). The hypothesis of null-response conflict in Stroop matching tasks has been reinforced by fMRI studies

that did not find anterior cingulate cortex (ACC) activation for the Stroop matching task (Mitchell 2006; Zysset et al. 2001). These results have led to the supposition that the Stroop matching task has some particular characteristics that make it distinct from other Stroop-like tasks. The ACC activation has been consistently related to response-conflict monitoring (Botvinick et al. 1999, 2001) or response-related aspects of attention selection (Liu et al. 2006; Milham and Banich 2005; Silton et al. 2010) with other Stroop-like tasks.

In addition to fMRI studies, other Stroop-like projects have applied the ERP technique. Two principle, late interference-related response components have been consistently indentified: the N450 and the late positive complex (LPC) (Atkinson et al. 2003; Liotti et al. 2000; Markela-Lerenc et al. 2004; Rebai et al. 1997; West and Alain 1999). The N450 has been considered a reflection of the detection and/or resolution of response conflict, and it has been related to ACC activity (Hanslmayr et al. 2008; Liotti et al. 2000; West et al. 2004). The LPC has been associated with late semantic processing (Liotti et al. 2000). The congruency effect is scarce among sensory ERP components (Ilan and Polich 1999), which suggests that the Stroop interference occurs exclusively at later stages during response selection, rather than sensory input processing. Alternatively, fMRI studies have also considered the involvement of early feature attentional processing (Polk et al. 2008).

Recently, Goldfarb and Henik (2006) have conducted a more profound analysis of the Stroop matching task by using a between-feature matching strategy (word–color matching). They compared the reaction times (RTs) in response to five different combinations of congruent and incongruent conditions: two conditions were for the "same" and three were for "different" responses [see Goldfarb and Henik (2006) for details]. They found that "same" and "different" responses differed in relation to the congruency effect that was observed: there were shorter RTs for incongruent stimuli than congruent stimuli for the "different" condition. According to their interpretation, participants erroneously make an irrelevant match between the relevant and irrelevant attributes of the Stroop stimulus, and this error interferes in response selection. Thus, congruent and incongruent Stroop stimuli would generate a tendency to respond to "same" and "different", respectively. Conflict would occur when the Stroop stimulus is congruent but the correct response is "different" and vice versa (Stroop stimulus is incongruent, and correct response is "same"). The authors suggested a reevaluation of the previous theory that considered semantic competition as the major source of conflict in the Stroop matching task.

The irrelevant matching reported by Goldfarb and Henik (2006) could be an essential step for triggering conflict in subsequent levels of processing such as decision-making

and response selection. Irrelevant feature integration during matching is a plausible explanation for irrelevant matching because the irrelevant attribute of the Stroop stimulus is in the same feature domain as the relevant stimulus. For instance, to make a word–color matching decision for the word from the Stroop stimulus with the color of a colored patch, participants must ignore the color of the Stroop stimulus, which is in the same feature domain as the target color. Additionally, the irrelevant color has the advantage of being placed in the same location as the word to be matched, while the relevant color patch is less favored by spatial attention. In other words, it must be difficult to ignore an attribute which is being favored by spatial attention and that is in the same feature domain of another stimulus used as target.

The inability to pay attention to exclusively task-relevant features, while ignoring a competing task-irrelevant feature could be the reason why participants mistakenly performed an irrelevant feature match during the task. Previous research using event-related potentials, which provide a high temporal resolution of cortical function, has suggested that early ERP components such as P1/N1 are sensitive to spatial and feature-based selective attention (Hillyard and Munte 1984; Mangun 1995; Zhang and Luck 2009). Specifically, the pattern of more negative N1/P2 amplitudes during the nonspatial selection of stimulus features (e.g., color, shape, motion) has been referred to as "selection negativity" or SN, which has an onset latency between 140 and 180 ms poststimulus (Anllo-Vento and Hillyard 1996; Anllo-Vento et al. 1998). This wave likely reflects the electrophysiological correlate of the way a particular feature is selectively processed according to its task relevance. The source of the wave is probably located in the extrastriate cortex (Schoenfeld et al. 2007).

There have been reports that SN amplitude increases as a function of the number of attended features (Keil and Muller 2010; Smid et al. 1999). For instance, Keil and Muller (2010) observed a greater difference wave in the traditional SN window (160–220) when the selection of a stimulus feature (e.g., size) was accompanied by another attended target feature (e.g., color), compared to selection of a feature in otherwise unattended stimuli (e.g., size selection when the color of the object is unattended). The role of SN on perceptual decisions based on the conjunction of cross-dimensional stimulus features, such as color and shape, has been previously investigated with a go/no-go Stroop-like task (Kopp et al. 2007). Kopp et al. (2007) used a visual target identification task, in which subjects identified target-compatible features in color and shape domains. They observed higher SN amplitude when the stimuli that elicited a no-go response shared a feature characteristic (in color or shape domain) with the stimuli that elicited a go-response.

In the present work, we tested the hypothesis that the to-be-ignored feature of the Stroop stimulus is perceptually processed, thus interfering in the between-feature matching task. Along these lines, we predicted that a modulation in earlier segments of the ERP occurs, especially by feature-based attention to stimuli during congruent and incongruent conditions. That Stroop-like interference may not exclusively occur at stages of response selection (Hanslmayr et al. 2008), but also during sensory processing, could indicate serious implications for the established postulation. Moreover, we manipulated the SOA between stimuli to investigate whether the attenuation of the congruency effect with increasing SOA, which was previously observed in behavioral Stroop matching task studies, was also related to variations in ERP visual components.

Methods

Participants

Data were collected from 37 (age: 21 ± 1.23; 7 male) graduate psychology students at the University of Granada. All participants were right-handed and had normal or corrected-to-normal vision. They were naive to the goals of the experiment. All procedures were approved by the local ethics committee, and written informed consent was obtained from the participants prior the study.

Stimuli and task

The stimuli were a colored word in congruent or incongruent color ink (Stroop stimulus) and a color–word in white ink (Fig. 1). We have chosen to use a color–word matching task (i.e., compare the color of the Stroop stimulus with a color–word in neutral ink) instead of a word–color matching task (i.e., compare the word from the Stroop stimulus with a colored patch) to test the irrelevant matching hypothesis. Although Goldfarb and Henik (2006) used the word–color matching task, this form of the task makes it difficult to obtain satisfactory physical control, because it is hard to equalize color distribution across conditions. As physical control is important to the early ERP components on which we were focusing, we chose to use a color–word comparison, which also required between-feature matching. To make a comparison between the color of the Stroop stimulus and the color–word in neutral ink, subjects must ignore the word presented in the Stroop stimulus, which is also a color–word. Many other Stroop matching task studies have also used the color–word comparison (Dyer 1973; Mitchell 2006; Simon and Baker 1995; Treisman and Fearnley 1969; Zysset et al. 2001). Although we recognize that this strategy limits comparison

Fig. 1 Sequence of events and duration of stimuli. The first stimulus (S1) was a color–word (YELLOW, BLUE, or RED) in a congruent or incongruent color ink. The second stimulus (S2) was a color–word in white ink. Subjects would press a key only if S1 and S2 matched (Go). Only Go conditions [*Go/incongruent* (1) and *Go/congruent* (2)] were analyzed, and they represented 80% of total trials. *No-go/congruent* (3), *No-go/incongruent-unrelated* (4), and *No-go/incongruent-related* (5) represented 20% of total trials. "Related" and "unrelated" refer to the relationship between the color–word of the Stroop stimulus (S1) and the color–word of S2. S1 and S2 stimuli could be presented simultaneously or with a 400 or 1,200 ms SOA
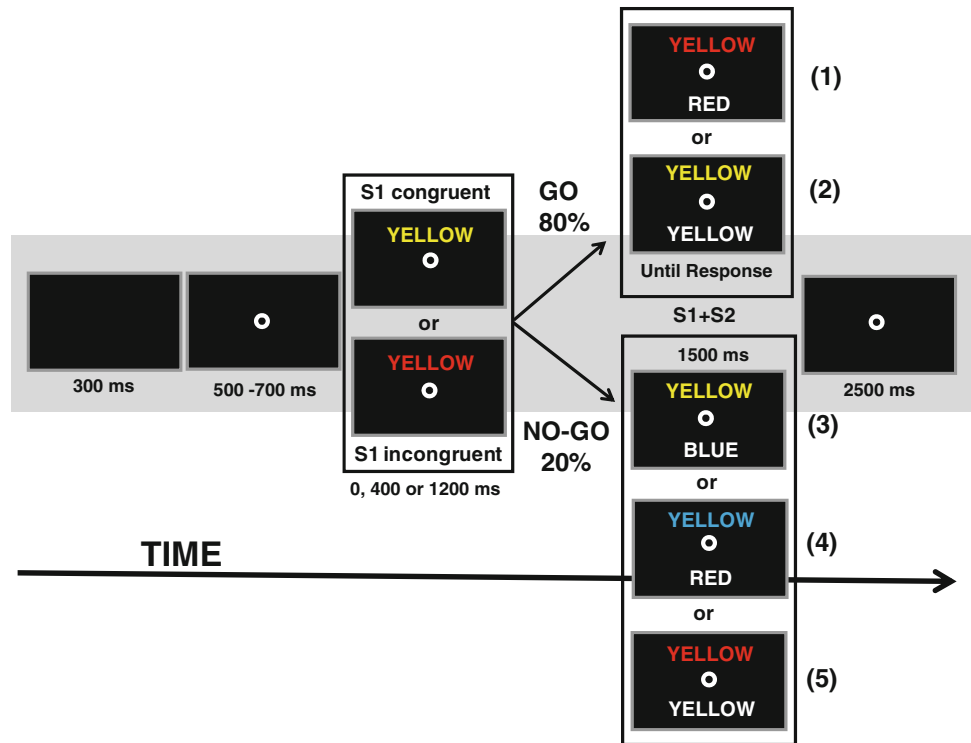
between our study and Goldfarb and Henik (2006) study, it still allows us to test the irrelevant matching hypothesis.

The two stimuli were presented simultaneously or with an SOA of 400 or 1,200 ms between them. Each trial began with a blank screen (300 ms) followed by the appearance of an empty circle used as a fixation point. In SOA-400 and SOA-1200 conditions, after approximately 500–700 ms from fixation onset, the first stimulus (S1) was presented 1.5° above fixation. S1 was a color–word (YELLOW, RED or BLUE), printed in yellow, red, or blue ink (Fig. 1, stimuli above fixation). After an interval of 400 or 1,200 ms from S1 onset, the second stimulus (S2) was presented 1.5° below fixation, and it was a color–word printed in white ink (Fig. 1, stimuli below fixation). Both S1 and S2 remained on the screen until a manual response occurred. In the SOA-0 condition, S1 and S2 were presented simultaneously after fixation point onset. Each letter composing the words measured 0.9° × 0.9° of the visual angle. Once both stimuli were presented on the screen (for all SOAs), participants were asked to compare the color ink of S1 to the word of S2 and to press a key if they were the same. If they did not match, no response was required (go/no-go task). Go-trials occurred in 80% and no-go trials in 20% of the trials. This design was chosen instead of a choice response design with "same" and "different" responses in order to reduce the number of conditions that had to be analyzed, permitting a larger number of trials per condition and therefore improving the signal-to-noise ratio. However, despite the absence of an overt response, the

"different" condition occurred in 20% of our trials because it was important to minimize anticipatory behavior by the participants. Response times were not analyzed for "different" judgments. In addition, congruent and incongruent conditions in the "same" and "different" trials were not grouped together to avoid misunderstandings in interpreting the results (Goldfarb and Henik 2006). We compared two distinct conditions with an error analysis for Go trials: *Go/congruent* and *Go/incongruent*; and three conditions for No-go trials: *No-go/congruent*, *No-go/incongruent-unrelated*, and *No-go/incongruent-related* (see Fig. 1). The experimental session had 6 blocks of 90 trials each (seventy-two Go trials and eighteen No-go trials) with 1 or 2 min of rest between blocks. Half of the Go trials were congruent, and half were incongruent. Therefore, there were 36 *Go/congruent* conditions and 36 *Go/incongruent* conditions per block (12 for each SOA). There were 6 *No-go/congruent*, 6 *No-go/incongruent-related*, and 6 *No-go/incongruent-unrelated* conditions per block that were equally distributed among the SOAs. The presentation of conditions for each block was randomized, and block order was counterbalanced between subjects. Each trial began after an inter-trial interval (ITI) of 2,500 ms. Anticipatory (RT shorter than 100 ms), slow (RT greater than 1,500 ms), and incorrect key-press responses were considered errors and were excluded from further behavioral and ERP analyses. The experiment was conducted in a sound-attenuated room under dim ambient light. Participants sat in front of an LCD monitor with their head

positioned by means of a chin rest approximately 57 cm from the display. A microcomputer running E-Prime v1.2 (Psychological Software Tools, Inc.) timed the presentation of the stimuli, delivered trigger codes, and recorded key presses.

Behavioral analysis

We conducted a congruency (*Go/congruent* and *Go/incongruent*) X SOA (0, 400 and 1,200 ms) two-way repeated-measures ANOVA on the correct RT data. Two separate error rate ANOVAs were performed for Go and No-go trials. For Go-trials, we performed a two-way repeated measured ANOVA with Error type (anticipation and slow responses) × congruency (*Go/congruent* and *Go/incongruent*) as factors. For No-go trials, we performed a one-way repeated measures ANOVA with congruency (*No-go/congruent*, *No-go/incongruent-related*, and *No-go/incongruent-unrelated*) as a single factor.

Electrophysiological recording and analysis

We recorded electroencephalogram (EEG) using an Asalab (Advanced Neuro Technologies) recording system with thirty-two (Ag/AgCl) electrodes embedded in a cap in the following electrode sites from the 10–20 system: FPz, FP1, FP2, Fz, F7, F3, F4, F8, FC5, FC1, FC2, FC6, Cz, C3, C4, T7, T8, CP5, CP1, CP2, CP6, Pz, P3, P7, P4, P8, POz, Oz, O1, O2, M1, and M2. Additionally, two electrodes were placed on the outer canthi to detect horizontal eye movement. All electrodes were referenced to Cz during the recording session and then referenced again offline to the average reference. The sample rate was 1,024 Hz during data acquisition, and the data were resampled at 256 Hz for analysis. Impedance was kept below 10 kΩ for all electrodes. The data were filtered offline using 0.3 Hz highpass and 70 Hz low-pass digital filters. Offline analysis of the data, including the removal of eye movement artifacts, was performed using the EEGLAB v5.03 toolbox (Delorme and Makeig 2004) with Matlab v7.0 (Math-works, Natick, MA). The data were epoched from 100 ms pre-S1 onset to 1,200 ms post-S2 onset. Thus, the epochs had a distinct length according to SOA conditions as follows: SOA-0 (1,300 ms), SOA-400 (1,700 ms), and SOA-1200 (2,500 ms). For all SOA conditions, the baseline corresponded to the 100 ms period preceding S1 onset. Epochs containing voltage deviations larger than 100 μV relative to baseline for any of the electrodes were rejected. Eye movement artifacts were removed from the data using Independent Component Analysis (Jung et al. 2000).

Separate averages were calculated for ERPs with incongruent and congruent stimuli (for Go trials) in the three SOAs. P1 and N1 components were measured for the parietal–occipital electrodes (O1, O2, Oz, POz, P7, P3, Pz, P4, P8), and their peak amplitudes were quantified in the 80–120 (Akyurek et al. 2010a, b) and 160–200 (Keil and Muller 2010) time-windows after S2 onset.

A congruency (*Go/congruent* and *Go/incongruent*) × Electrode (O1, O2, Oz, POz, P7, P3, Pz, P4, P8) two-way repeated measures ANOVAs were conducted separately for each SOA. When appropriate, a post hoc analysis using the Newman–Keuls test was also performed, and a Greenhouse–Geisser epsilon correction for nonsphericity was applied to both the behavioral and the EEG data. The alpha level adopted for statistical significance was $\alpha = 0.05$.

To further investigate a possible correspondence between behavioral and N1 temporal modulations, we computed the linear trend pattern obtained for behavioral and ERP data as a function of SOA. Congruency effects (delta = *Go/incongruent* minus *Go/congruent*) for behavioral and ERP data were investigated through one-way repeated measures ANOVAs with SOA (0, 400, 1,200 ms) as factor. For ERP data, this repeated measures one-factor ANOVA was computed for each parietal–occipital electrode separately (O1, O2, Oz, POz, P7, P3, Pz, P4, P8). We have focused our ERP analyses on the delta waves because in the present experimental design, at SOA-400, the ERPs for successive stimuli overlap with differing amounts of distortion related to SOA-0 and SOA-1200. Although there are other methods for deconvolving differential overlap in the ERP waveforms (Woldorff 1993), the approach used in the current study was designed to restrict direct comparisons between SOAs to the delta congruency as proposed by Appelbaum et al. (2009). An equivalent amount of overlap was present for the incongruent and congruent trials within a given SOA. Therefore, evaluating the difference wave has been demonstrated to be an effective approach in these instances (Appelbaum et al. 2009).

To take advantage of the topographical information in the ERP signal and to relate behavioral and electrocortical linear trend patterns along SOAs, we performed additional analysis on significant ANOVA results with correlation maps (Keil et al. 2008). The ERP data and RTs were combined across SOAs to form a linear trend index for each participant. Specifically, RT differences (*Go/incongruent* minus *Go/congruent*) were treated as follows: LINEAR TREND INDEX = [RTdiff (SOA-0) − RTdiff (SOA-400)] + [RTdiff (SOA-400) − RTdiff (SOA-1200)]. This index becomes larger if participants show a maximum RT increase for incongruent Stroop displays during SOA-0 trials and show a linear decrease in the congruency effect (see Fig. 3 for a better view of the linear pattern). The same logic was applied to ERP differences in the SN window, resulting in a measure of linear amplitude reduction in the difference wave (incongruent minus

congruent) across SOAs. Pearson correlations between both linear indices were calculated and plotted on the scalp (see Fig. 4 for a better view of the scalp correlation plot).

Results

Behavioral data

Error analysis

The overall mean percentage of errors was 2.27% (453 errors in 19,980 trials): 114 errors in Go-trials and 339 errors in No-go trials. The ANOVA for Go-trials revealed a main effect of Error type [$F(1, 36) = 16,09$, $P < 0.001$; $\varepsilon = 1.00$] and congruency [$F(1, 36) = 23.62$, $P < 0.001$; $\varepsilon = 1.00$] as well as for the interaction between these factors [$F(1, 36) = 14.48$, $P < 0.01$; $\varepsilon = 1.00$]. Post hoc analysis revealed that slow responses were more frequent in the *Go/incongruent* trials (89 errors in 15,984 trials; 0.56%) than in the *Go/congruent* trials (19 errors; 0.12%; $P < 0.001$). The analysis of anticipated trials showed that the difference between *Go/congruent* (0.01%) and *Go/incongruent* (0.04%) conditions was not significant ($P = 0.262$). For No-go trials, a significant effect was found for condition [$F(1, 52) = 15, 35$, $P < 0.001$; $\varepsilon = 0.72$]. Post hoc analysis revealed that participants committed more errors in *No-go/congruent* trials (169 errors in 3,996 trials- 4.23%) than in *No-go/incongruent-unrelated* (70 errors—1.75%) and *No-go/incongruent-related* (100 errors—2.50%) trials ($P < 0.001$ for both comparisons). There was no difference between the two incongruent No-go conditions ($P = 0.106$). Thus, error analyses indicated that the incongruent trials elicited more errors during *Go* responses, while the opposite pattern was observed for the *No-go* trials (*No-go/congruent* condition elicited more errors).

Reaction time analysis

The ANOVA for response time showed that congruency and SOA were significant sources of variance, [$F(1, 36) = 166.85$, $P < 0.001$; $\varepsilon = 1.00$] and [$F(1, 49) = 1043.47$, $P < 0.001$; $\varepsilon = 0.67$], respectively. The interaction was also significant [$F(2, 66) = 264.82$, $P < 0.001$; $\varepsilon = 0.91$]. RTs obtained for *Go/congruent* trials were shorter than those obtained for *Go/incongruent* trials (500 vs. 574 ms). Post hoc analysis showed that RTs also tended to decrease as SOA increased (727 vs. 478 vs. 406 ms, respectively; $P < 0.001$ for all comparisons). *Go/incongruent* and *Go/congruent* conditions were significantly different at SOA-0 (831 vs. 624 ms, respectively); at SOA-400 (504 vs. 452 ms, respectively), and at SOA-1200 (389 vs. 424,

respectively; $P < 0.001$ for all comparisons). Thus, the interaction indicated that the strongest difference between conditions was elicited at SOA-0. In addition, there was attenuation at SOA-400, and an inversion of the congruency effect occurred at SOA-1200, with the *Go/congruent* condition eliciting greater responses.

Electrophysiological data

The P1 and N1 following the S2 stimuli were maximal at the parieto–occipital scalp areas. The ANOVA of the P1 amplitude revealed a significant main effect for Electrode at SOA-0 [$F(4, 138) = 19.29$, $P < 0.001$; $\varepsilon = 0.48$], SOA-400 [$F(4, 128) = 5.42$, $P < 0.001$; $\varepsilon = 0.44$], and SOA-1200 [$F(4, 130) = 24.70$, $P < 0.001$; $\varepsilon = 0.45$]. There was not a main effect for congruency at SOA-0 [$F(1, 36) = 0.05$, $P = 0.818$; $\varepsilon = 1.00$], SOA-400 [$F(1, 36) = 1.29$, $P = 0.26$; $\varepsilon = 1.00$], or SOA-1200 [$F(1, 36) = 0.35$, $P = 0.56$; $\varepsilon = 1.00$]. The interaction did not reach significance at SOA-0 [$F(4, 151) = 0.55$, $P = 0.71$; $\varepsilon = 0.52$] and at SOA-400 [$F(4, 150) = 1.86$, $P = 0.12$; $\varepsilon = 0.52$]. The interaction was significant at SOA-1200 [$F(4, 137) = 5.06$, $P < 0.01$; $\varepsilon = 0.47$], and the post hoc analysis revealed that the amplitude of *Go/incongruent* and *Go/congruent* conditions differed at electrodes P4 and P7 ($P < 0.001$ for both).

The N1 component amplitude yielded a significant main effect for the Electrode at SOA-0 [$F(3, 105) = 17.85$, $P < 0.001$; $\varepsilon = 0.36$], SOA-400 [$F(3, 94) = 6.13$, $P < 0.001$; $\varepsilon = 0.33$], and at SOA-1200 [$F(3, 101) = 13.60$, $P < 0.001$; $\varepsilon = 0.35$] as well as a significant main effect for congruency at SOA-0 [$F(1, 36) = 6.27$, $P < 0.05$; $\varepsilon = 1.00$] and SOA-1200 [$F(1, 36) = 9.04$, $P < 0.01$; $\varepsilon = 1.00$]. The *Go/congruent* condition elicited a greater N1 component in relation to the *Go/incongruent* condition at SOA-0. The opposite pattern was observed at SOA-1200, where the *Go/incongruent* condition elicited a greater N1. There was no main effect for congruency at SOA-400 [$F(1, 36) = 2.65$, $P = 0.11$; $\varepsilon = 1.00$], but the interaction was significant [$F(4, 152) = 2.38$, $P < 0.05$; $\varepsilon = 0.54$]. Post hoc contrasts at SOA-400 showed that the amplitude of the N1 component was greater in the *Go/congruent* condition than the *Go/incongruent* condition for electrodes O1, Oz, and O2 ($P < 0.05$ for all). The interaction was not significant at SOA-0 [$F(4, 149) = 2.16$, $P = 0.07$; $\varepsilon = 0.52$] and SOA-1200 [$F(5, 172) = 1.85$, $P = 0.11$; $\varepsilon = 0.60$]. Thus, similar to the pattern observed for reaction time, the dynamics of the N1 congruency effect are SOA-related, demonstrating an inversion of the effect at SOA-1200 in relation to SOA-0 and SOA-400. The *Go/congruent* condition consistently elicited a greater N1 amplitude in SOA-0, and an inversion occurred at SOA-1200 (the *Go/incongruent* condition elicited a greater

N1). ERP waveforms and topographical maps at P7 from the overall average of all subjects for both *Go/incongruent* and *Go/congruent* conditions in the three SOAs are shown in Fig. 2.

Electrophysiological vs. behavioral

There was a significant effect for SOAs on RT measures [$F_{(2, 66)} = 264.81$, $P < 0.001$, $\varepsilon = 0.91$] with delta congruency gradually decreasing from SOA-0 to SOA-1200, as confirmed by post test linear trend analysis

[$F_{(1, 109)} = 379.8$, $P < 0.001$; see Fig. 3, left panel]. Significant congruency effects for SOAs on N1 amplitudes were also observed at the parietal–occipital electrodes: P7 [$F_{(2, 72)} = 12.85$, $P < 0.001$; $\varepsilon = 0.88$], P3 [$F_{(2, 72)} = 10.64$, $P < 0.01$; $\varepsilon = 0.83$], POz [$F_{(2, 72)} = 3.91$, $P < 0.05$; $\varepsilon = 0.99$], O1[$F_{(2, 72)} = 6.62$, $P < 0.010$; $\varepsilon = 0.98$], Oz [$F_{(2, 72)} = 3.20$, $P < 0.05$; $\varepsilon = 0.99$], and O2 [$F_{(2,7\ 2)} = 3.36$, $P < 0.05$; $\varepsilon = 0.95$]. A significant linear trend with delta congruency gradually increasing from SOA-0 to SOA-1200 was found at the following electrodes: P7 [$F_{(1, 109)} = 25.35$, $P < 0.001$]; P3 [$F_{(1, 109)} = 16.34$,

Fig. 2 Right—Grand mean topographical distribution of the N1 averaged across a time window of 160–200 ms post-S2 onset for *Go/incongruent* and *Go/congruent* differences (*Go/incongruent* minus *Go/congruent*: congruency effect). Left—Grand-average event-related potential (ERP) waveform elicited by *Go/incongruent* and *Go/congruent* conditions at P7 electrode at SOA-0 (*top*), SOA-400 (*middle*), and SOA-1200 (*bottom*). The time scale represents the epoch pre- and post-S2 onset for each SOA
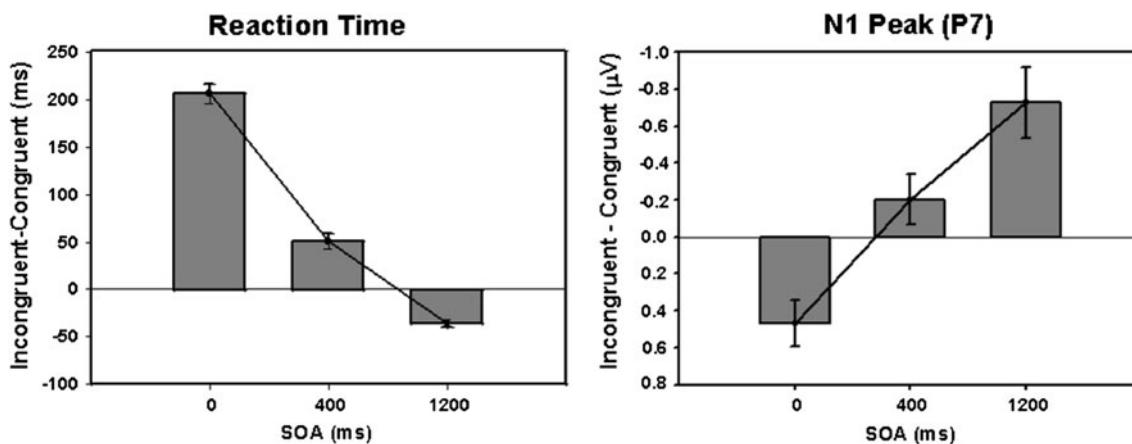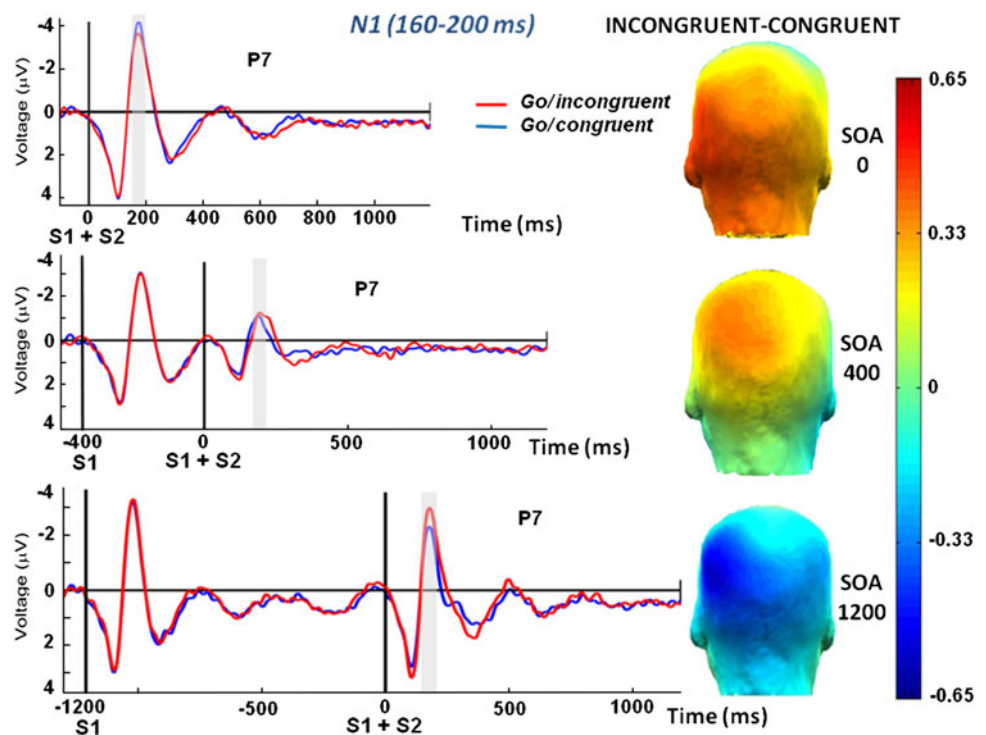
Fig. 3 Left—Reaction time delta (*Go/incongruent* minus *Go/congruent*) along SOAs. Right—N1 delta (*Go/incongruent* minus *Go/congruent*) peak amplitude along SOAs. There was a linear trend in the opposite direction for RT and N1 congruency effects. RT congruency effect decreased, and the N1 congruency effect increased along SOAs. *Error bars* indicate the standard error of the mean
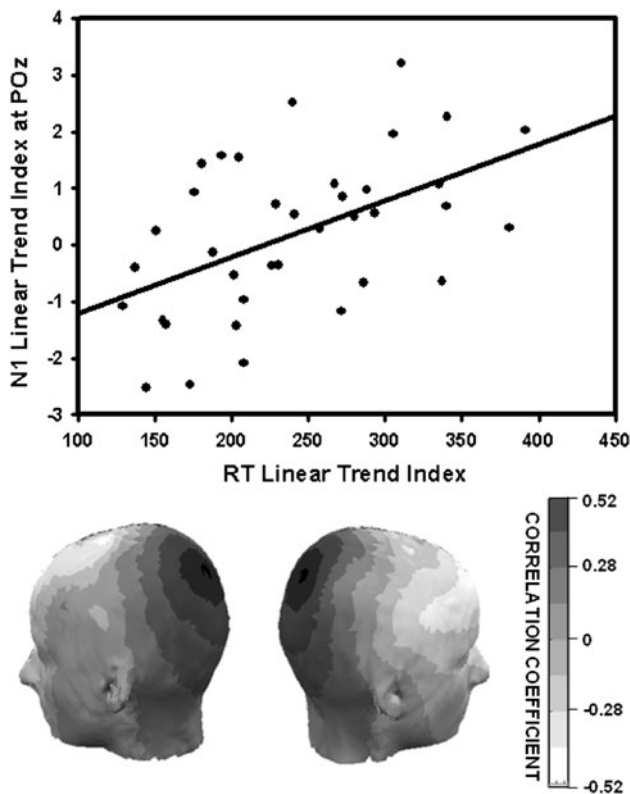
Fig. 4 Correlation scatter plot (*top*) obtained for POz and a rank-correlation map (*bottom*) showing the relationship between the N1 and the RT congruency linear trend indexes. The N1 amplitude linear index increased as the RT linear trend index increased, and this correlation was maximal at POz ($r = 0.51$, $P < 0.05$)

$P < 0.001$]; POz [$F(1, 109) = 6.26$, $P < 0.05$]; O1[$F(1, 109) = 5.35$, $P < 0.05$]; Oz [$F(1, 109) = 4.47$, $P < 0.05$]; and O2 [$F(1, 109) = 4.48$, $P < 0.05$]. The right panel of Fig. 3 illustrates results for the P7 electrode.

To further elucidate the relationship between RT and the N1 congruency effect along SOA, we performed a correlation analysis across the individual linear trend index obtained for the N1 amplitude at all electrodes and the same index calculated for behavioral data (see method). This procedure yielded correlation maps highlighting electrode sites that were related to changes in congruency linear trend indexes for RT across N1 amplitude. This correlation was maximal at the POz electrode ($r = 0.51$, $P < 0.05$, see Fig. 4).

Discussion

The Stroop matching task is an interesting, if somewhat overlooked, version of the Stroop phenomenon. Although many behavioral aspects involved in this task have been explored, there are few neural correlates of such behavioral findings. To study the mechanisms involved in Stroop matching tasks, we measured this modified Stroop effect along different SOAs by combining behavioral and brain-recording methods. Other studies that have used functional brain imaging to examine metabolic changes during this task have grouped together "same" and "different" responses (Mitchell 2006; Zysset et al. 2001). In order to provide unambiguous results, we evaluated response times, error rates, and early event-related potentials components by analyzing the "same" responses trough a go/no-go approach. We found that early negativity in the N1/P2 time segment (160–200 ms) was more negative for the congruent than the incongruent condition during simultaneous S1/S2 presentation (SOA-0). The size and direction of the congruency effect (i.e., incongruent minus congruent) were reliably affected by SOA between S1 and S2, showing an opposite pattern at SOA-1200. The modulation of the congruency effect along SOA was found only for N1 and not for P1, which may be related to the discriminatory nature of the task (Vogel and Luck 2000). These results suggest a major link between N1 and behavioral responses. The pattern of results found for N1 parallels and correlates with the behavioral results, where the RT for the congruent condition was shorter than the incongruent condition at SOA-0, and an inversion (shorter RTs for incongruent than congruent trials) was found at the longest SOA.

During the Stroop matching task, the feature (word) that was irrelevant at the S1 position was also the target at the S2 position. Thus, the distracter–word represented a potentially relevant stimulus that shared common features with the target–word and had the advantage of being in the same spatial location as color. We propose that color processing activated the representation of the word related to this specific color, facilitating the processing of the target–word and, although not desirable, the processing of the distracter–word. In a behavioral study, Wuhr and Waszak (2003) have explored this issue using an elegant approach. The participants had to name the color of one of two overlapping colored rectangles presented at the center of a screen, while ignoring the incongruent color–words that appeared as parts of the relevant object, as parts of the irrelevant object or in the background. Stroop interference was significantly larger when the incongruent words were part of the relevant object. Their results support the hypothesis that feature-based selection is associated with amplification in the processing of all the features of the selected object, including the irrelevant features (Wuhr and Waszak 2003). This conclusion has also been demonstrated through ERP studies that showed an enhancement in the amplitude of early ERP components for task-irrelevant features when the features shared common characteristics with the target (Zhang and Luck 2009). Based on these findings, we can presume that the N1 effect could reflect an overall feature facilitation triggered by the target features.

This effect would occur especially when the target and distracter words were exactly the same as the color (at congruent condition there would be shorter reaction times). The effect would also arise when there is simultaneous competition between the target–word (S2) and distracter–word (S1) feature values (SOA-0).

One could argue that the N1 component reflects facilitation promoted by word repetition in the congruent condition (a word–word effect) regardless of the instructions to pay attention to the words or to the color. However, many works have shown that the Stroop matching task effect is only robust for between-feature matching (color–word or word–color) and not for within-feature matching (word–word or color–color) (Luo 1999; Simon and Baker 1995; Sugg and McDonald 1994). The hypothesis that the N1 amplitude effect observed is related to a between-feature behavioral interference was reinforced through the SOA variation that was applied in our study. We observed a linear increment of N1 delta (incongruent minus congruent) peak amplitude along the SOAs (from the highest to the lowest behavioral conflict conditions). This trend provides evidence that the N1 component may be related to undesirable distracter processing that is maximal during SOA-0; otherwise, we should have been unable to observe a correspondence between N1 and behavioral congruency data as a function of task variations such as SOA.

One possibility is that when relevant and irrelevant attributes are in the same feature domain (e.g., both are words in the case of a color–word matching), distracter–word processing could induce an irrelevant matching and a conflict in other stages of processing such as in the response level. This conclusion agrees with task-conflict theory (Goldfarb and Henik 2006, 2007; MacLeod and MacDonald 2000). According to this theory, during a Stroop task, an irrelevant task (word reading) could interfere with the relevant task (color naming). In the present study, the irrelevant task was the comparison between the color of the Stroop stimulus and the distracter–word. Further evidence for this interpretation has emerged from error analysis of our data. We found that the *No-go/congruent* condition elicited a greater percentage of error than the *No-go/incongruent* conditions. It is possible that for the *No-go/congruent* condition, subjects are inclined to respond, generating more errors because of the initial facilitation promoted by the distracter–word in this condition. The ERP results of Kopp et al. (2007) reinforce this interpretation because they found neural-correlates of feature-based attentional selection affecting response-decisions, through a go/no-go approach.

This hypothesis could also offer an explanation for the lack of the congruency effect normally found during within-feature (word–word or color–color) matching tasks (Luo 1999; Sugg and McDonald 1994). During a within-

feature matching task, the relevant stimuli are in the same feature domain and the distracter is in a different feature domain and could be easily gated by attention, thereby avoiding the occurrence of a conflict during feature-integration processing and preventing the irrelevant task. Future studies should test if the N1 amplitude during incongruent and congruent conditions would be indistinguishable in this case, regardless of the SOA.

A prior study has shown that the feature-based attention effect is much stronger when attended and ignored stimuli are presented simultaneously (Zhang and Luck 2009). During simultaneous stimuli displays, there is a greater chance of relevant and irrelevant stimuli to become integrated into a single event. When S1 and S2 are processed as two separate events, there is a failure to integrate the events, leading to a modulation of the N1 amplitude (Akyurek et al. 2010a, b). In agreement with these observations, we found that the N1 congruency was modulated as a function of SOA and that this SOA variation affected behavioral responses in a correspondent fashion. Flowers (1975) observed similar temporal modulation on behavioral congruency by using SOAs ranging from 120 to 800 ms in a Stroop matching task. At SOA-800, he found the same pattern of reversal that we observed at SOA-1200, although the reversal was not significant (Flowers 1975).

Regarding the reversal effect found for both ERP and the behavioral data at SOA-1200, one possibility is that during SOAs, there is a controlled attention effort to gate distracter input and maintain the overall task goal according to instruction. In other words, controlled attentional mechanisms may be used to efficiently eliminate the distracter influence and improve performance in the face of conflict. Considering that the distracter–word and the target–word (S2) are the same in the congruent condition, it is plausible that at the longest SOA, there is an overall inhibition for this condition in opposition to the facilitation observed during simultaneous presentation. In fact, we observed electrophysiological evidence of this interpretation because the N1 component was affected by SOA, which showed an opposite pattern in SOA-1200 in relation to SOA-0, and this result paralleled the RT findings. Therefore, the matching feature decision seems to be initially driven by incoming information, but strongly influenced by higher cognitive processes when extra time is allowed. In essence, the longer time appears to promote an overall inhibition of distracter-related information. This interpretation is supported by evidence of top-down attentionally mediated distracter inhibition in the extrastriate cortex in a study using event-related functional magnetic resonance imaging (Slotnick et al. 2003). This evidence is consistent with the idea of enhanced processing in attended features areas concomitant with the suppression of distracter features during Stroop-like tasks (Polk et al. 2008).

In conclusion, the present study provided information about the mechanisms involved in Stroop matching tasks. A strong functional relationship between ERP data and behavioral performance was suggested by the remarkably linear relationship between the congruency effect observed in the N1 amplitude and RT across SOAs. An explanation may be the enhancement of early processing of stimuli when target and nontarget features are the same, thereby promoting facilitation for "same" responses. This initial facilitation is overcome when the SOA allows for extra processing of the relevant and irrelevant features. This trend may indicate the deployment of attentional resources that gate the irrelevant feature, thus causing an overall inhibition when the target–word and distracter–word are the same during long SOAs. Future studies are necessary to investigate if these electrophysiological data occur when "different" responses are also collected.

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