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**Behavioral and electrophysiological investigation of semantic and response conflict in
the Stroop task**

Maria Augustinova¹, Laetitia Silvert¹, Ludovic Ferrand¹, Pierre Michel Llorca² and Valentin
Flaudias²

¹CNRS and Université Blaise Pascal, Clermont-Ferrand, France

²CHU Clermont-Ferrand and Université d'Auvergne, Clermont-Ferrand, France

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Corresponding author:

Maria Augustinova

CNRS and Université Blaise Pascal

Laboratoire de Psychologie Sociale et Cognitive (LAPSCO – UMR CNRS 6024)

34, avenue Carnot

63037 Clermont-Ferrand

FRANCE

E-mail: maria.augustinova@univ-bpclermont.fr

Phone: + 33 473 406 257

Fax: + 33 473 406 114

Abstract

By combining the semantic Stroop paradigm (e.g., Klein, 1964) with single-letter coloring (SLC) procedure (e.g., Besner, Stolz, & Boutilier, 1997), this research investigated whether the frequently reported Stroop-related event-related potential (ERP) effect arising about 400ms after stimulus onset (N_{inc}) is sensitive to the semantic and/or the response conflict. Consistent with our past findings (e.g., Augustinova, Flaudias, & Ferrand, 2010), SLC speeded up RTs for standard-incongruent items only, indicating that SLC reduced response conflict that these (but not color-associated and neutral) items involve. N_{inc} amplitudes were more negative for standard-incongruent and color-associated than for color-neutral items. Importantly, this difference was not modulated by SLC. Hence the behavioral and ERP results conjointly suggest that the Stroop-related N_{inc} is sensitive to semantic rather than to response and/or general conflict.

Key words

Semantic conflict; Single-letter coloring, Stroop interference; N_{inc} ; Response conflict

The Stroop task (Stroop, 1935) requires participants to identify the font color of written characters as quickly and accurately as possible. Because the so-called incongruent Stroop words are displayed in a color that is different from the one they designate (e.g., *BLUE* displayed in green), it takes much longer to name their font colors than it does to name those of color-neutral items (e.g., *XXXX/DEAL* displayed in green).

In addition to reaction times (RTs), this effect also transpires in event-related potentials (ERPs) because incongruent Stroop words induce a stronger negativity than color-neutral items around approximately 400ms at fronto-central or centro-parietal electrode sites (e.g., Liotti, Woldorff, Perez, & Mayberg, 2000; Hanslmayr, Pastötter, Bäuml, Gruber, Wimber, & Klimesch, 2008; Coderre, Conklin & van Heuven, 2011). This Stroop-related ERP-effect varying in its distribution and morphology as a function of differences across experimental designs and response modes is referred to as N_{inc} , N450 or MFN (medial frontal negativity). It is likely to stem from the activation of the anterior cingulate cortex (ACC; Hanslmayr et al., 2008; Liotti et al., 2000), a brain area that is associated with processes involved in general conflict detection and resolution and is predominantly mobilized for incongruent items.

Although N_{inc} ¹ is probably the most conspicuous marker of Stroop interference, it is still rather unclear what specific process it is likely to reflect in the Stroop task namely because incongruent items involve two distinct types of conflict – each in an unknown amount (see e.g., Ferrand & Augustinova, 2014). Indeed, interference occurs in part because at the stimulus level, the meaning of the word-dimension (e.g., blue for *BLUE*_{green}) conflicts with the meaning of the color-dimension (e.g., green for *BLUE*_{green}). The additional interference occurs at the response level because the correct motor response (i.e., say

¹ In order to designate the relative negativity associated with the incongruent items compared to the neutral ones, we opted for the label N_{inc} as it is agnostic with regard to the exact timing (300-500 ms), topography and functional characteristics of this Stroop-related effect.

“green”/press green button) that is primed by the color-dimension conflicts with the incorrect motor response (say “blue”/press blue button) that is primed by the word-dimension.

Thus, perhaps because of N_{inc} proximity with the typical N400 effect (i.e., monophasic negativity that usually occurs at centro-parietal sites between 200 and 600ms after stimulus onset; e.g., Kutas & Federmeier, 2011), it is for some sensitive to semantic conflict (e.g., Coderre et al., 2011). For others however, it rather reflects the detection and/or resolution of response conflict (e.g., Appelbaum, Meyerhoff, & Woldorff, 2009) or the detection of (general) interference and the elicitation of central executive processes in response to it (Hanslmayr et al., 2008).

Moreover, the scarce empirical work that actually separated the contribution of each type of conflict (see above) to the overall Stroop interference is not much more clear-cut on this issue. On one hand, Szűcs and Soltész (2010) tend to conclude that N_{inc} was *not* related to the detection or resolution of response conflict. On the other hand, Killikelly and Szűcs (2013) suggest that N_{inc} is to general conflict even though they found no differences between the condition involving both types of conflict and the one involving the semantic conflict only. In sum, the question of whether N_{inc} , as a marker of Stroop interference, is actually sensitive to semantic conflict, response conflict or both still remains unanswered.

Therefore the present paper continues to investigate this issue within the so-called semantic Stroop paradigm (Klein, 1964; see also Neely & Kahan, 2001) that supplements standard Stroop words depicted above with words that are only associated with an incongruent color (e.g., *SKY* displayed in green). Contrary to standard-incongruent items (e.g., *BLUE*_{green}), these color-associated items still involve semantic conflict but they are free of response conflict².

² Because color-associates (*SKY*_{green}) are displayed in a color that is different from the one they are associated with (i.e., sky with blue), this color –which is retrieved when the word-dimension is read– subsequently conflicts with the meaning of the word’s color-dimension (i.e., green for *SKY*_{green}). But since color-associates do not

Thus, if standard-incongruent items elicit stronger negativity around 400ms than color-associated and color-neutral items and if the negativity elicited by these two latter kinds of item is similar, then this Stroop related N_{inc} effect is likely to be associated with response but not with semantic or general conflict. However, if both standard-incongruent and color-associated items elicit a similar negativity which is significantly stronger than that elicited by color-neutral items, then N_{inc} is likely to reflect semantic but not response or general conflict. Finally, if at around 400ms, standard-incongruent items elicit stronger negativity than color-neutral items with the negativity elicited by color-associated being between these two, then N_{inc} is likely to be sensitive to general conflict. The first specific goal of the present study was to test these competing predictions while using vocal responses.

Indeed, our past work using the semantic Stroop paradigm administered with vocal responses showed that latencies for standard-incongruent (but not for color-associated or neutral) items are significantly shorter when only a single letter (as opposed to all letters) in a word is colored in an incongruent color (e.g., green “E” in the word “*BLUE*” with “B”, “L” and “U” presented in gray or in another incongruent color from the response set, e.g., Besner, Stolz, & Boutilier, 1997). This pattern of results suggests that single-letter coloring (SLC) is likely to reduce response conflict that only standard-incongruent trials involve (e.g., Augustinova & Ferrand, 2007; Augustinova, Flaudias, & Ferrand, 2010; but see also Manwell, Roberts, & Besner, 2004 for a different result and ensuing explanation).

It is important to note that our investigation of Stroop-related N_{inc} can benefit greatly from the replication of such a reduction. If the Stroop-related N_{inc} effect is indeed sensitive to response and/or general conflict but not to semantic conflict, the stronger negativity around 400ms elicited by standard-incongruent items compared to both color-associated and color-neutral items when all letters are colored in an incongruent color (i.e., ALC condition) should

activate incorrect motor responses (e.g., say “blue”/press blue for *SKY_{green}*; e.g., Schmidt & Cheesman, 2005), their processing involves no response conflict.

be reduced in the SLC condition. However, if N_{inc} is sensitive to semantic conflict but not to response and/or general conflict, standard-incongruent and color-associated items should elicit a stronger negativity than color-neutral items at around 400ms in both the ALC and SLC conditions. The second specific goal of the present study was to test these competing predictions.

Method

Participants

Twenty-eight psychology undergraduates (24 females and 4 males, all native French-speakers reporting normal or corrected-to-normal vision) at Blaise Pascal University, Clermont-Ferrand (Mage = 18.9 years) took part in this experiment in exchange for financial compensation (€25).

Design and Stimuli

The participants completed each condition of a 3 (Stimulus-type: incongruent vs. color-associated vs. neutral) \times 2 (Coloring: ALC vs. SLC) within-subjects factors design. There were 30 trials in each condition that varied randomly within a single block of 180 experimental trials.

The stimuli (presented in lowercase Courier font on a white background subtending an average visual angle of 0.9° high \times 3.0° wide) consisted of six color words: *rouge* [red], *jaune* [yellow], *bleu* [blue], *vert* [green], *marron* [brown], and *orange* [orange]; six color-associated words: *tomate* [tomato], *maïs* [corn], *ciel* [sky], *salade* [salad], *chocolat* [chocolate], and *carotte* [carrot]; and six neutral words: *balcon* [balcony], *robe* [dress], *pont* [bridge], *chien* [dog], *train* [train], and *studio* [studio]. In half the trials, the entire letter string appeared in incongruent target colors. In the other half of the trials, only a single letter appeared in an

incongruent target color, with the remaining letters appearing in another incongruent color from the response set.

Apparatus and Procedure

The participants were seated approximately 50 cm in front of a 17-inch Dell color monitor. In both ALC and SLC conditions, their task was to name the color of a letter indicated by small arrows as quickly and accurately as possible while ignoring everything else in the display. To this end, they were instructed to concentrate on the fixation cross (“+”) that appeared in the center of the screen at the beginning of each trial for 450, 500 or 550ms. This was then replaced by small arrows (height of 1.2° of visual angle) displayed 0.6° above and below the position previously occupied by the fixation cross and subsequently occupied by the target letter. The arrows (i.e., spatial cues) remained on screen for 125, 150 or 175ms, after which the stimulus was displayed. Because the spatially pre-cued letter was randomly located at either the initial, middle, final or the optimal viewing position, the stimuli shifted horizontally from trial to trial in such a way that the spatially pre-cued letter always appeared in the same location as the preceding central fixation cue. The entire display remained on screen until a response was made. Before the presentation of the next fixation cross, a black dot appeared on screen for 1000, 1100, 1200 or 1300ms notifying the participants that they were free to blink. The duration of the above parameters varied randomly across trials in order to prevent a phase lock on trial timing. The participants were familiarized with these instructions during a set of twelve practice trials.

Stimulus presentation and behavioral data collection were controlled by E-Prime2.0. The participants’ naming latencies were measured to the nearest millisecond and recorded via a Koss 70dB microphone. The EEG signal from 64 active electrodes (extended 10–20 system) was recorded continuously using the BioSemi Active II System. Four additional electrodes were placed at the outer canthus of each eye and above and below the right eye to permit

bipolar recordings of horizontal and vertical EOG. EEG and EOG were acquired continuously relative to a “zero-Ref” setup (cf. <http://www.biosemi.com> for further information) at a rate of 512 Hz, amplified with a bandpass from 0.16 Hz to 100 Hz, and stored for off-line processing with BESA 5.2.3.

EEG data analysis

EEG recordings were re-referenced to the average reference and corrected for eye blinks using the spatial components method implemented in BESA. ERPs time-locked to the stimuli (−100ms to 600ms) were averaged separately for each channel and for each experimental condition and were digitally filtered at 35 Hz (24Db/octave, zero phase shift digital filter). Trials with signals exceeding $\pm 100\mu\text{V}$ and a gradient criterion of more than $75\mu\text{V}$ were rejected automatically.

A visual inspection of the grand-average waveforms for ALC incongruent and neutral trials revealed an enhanced fronto-central negativity for incongruent trials, which reached its maximum amplitude at around 430ms (see also Liotti et al., 2001). Thus, N_{inc} was quantified as the mean amplitude from 380 to 480ms at F1, F3, Fz, F2 and F4 for all the experimental conditions. The data from F1 and F3, on the one hand, and F2 and F4, on the other, were then averaged together, resulting in an additional 3-level (left vs. central vs. right) Location factor.

Results

Naming latencies greater than 3 *SDs* above or below each participant’s mean latency for each condition (i.e., less than 1% of the total data) were excluded from the analyses. The analysis of mean correct latencies subsequently revealed main effects of Stimulus-type [$F(2,54) = 33.63; p < .001, \eta_p^2 = .56$] and of Coloring [$F(1,27) = 6.13; p < .05, \eta_p^2 = .19$] as well as a Stimulus-type \times Coloring interaction [$F(2,54) = 7.36; p = .001, \eta_p^2 = .21$]³.

³ The same analysis on error rates only revealed the effect of Stimulus-type [$F(2,54) = 12.48; p < .001, \eta_p^2 = .32$; see Table 1].

The decomposition of this interaction first revealed that latencies for standard-incongruent and color-associated trials were significantly longer than those observed for color-neutral trials in both the ALC and SLC conditions (all $p_s < 0.05$, see Table 1), thus showing that both standard (e.g., $BLUE_{\text{green}} - DEAL_{\text{green}}$) and semantic interference (e.g., $SKY_{\text{green}} - DEAL_{\text{green}}$) occurred in all conditions.

<Table 1>

The decomposition of the overall Stimulus-type \times Coloring interaction also revealed that standard but not semantic interference was reduced by SLC (see Table 1)⁴ and that this reduction was solely due to significantly shorter latencies for standard-incongruent trials. Indeed, the simple main effect of Coloring was significant only for standard-incongruent trials [$F(1,27) = 15.40$; $p = .001$, $\eta_p^2 = .36$] but not for color-associated or color-neutral trials (both $F_s < 0.22$; $p > .65$, *ns*; see Table 1). Moreover, the contrasts between standard and color-associated incongruent stimuli (e.g., $BLUE_{\text{green}} - SKY_{\text{green}}$) which is the direct estimate of interference due to the response conflict only, remained significant in both ALC [$F(1,27) = 20.67$; $p < .001$, $\eta_p^2 = .44$] and SLC [$F(1,27) = 6.36$; $p < .05$, $\eta_p^2 = .19$] conditions. However, as expected, this response interference was reduced from 58ms in the ALC condition to 15ms in the SLC condition [$F(1,27) = 28.43$; $p < .001$, $\eta_p^2 = .51$, see Table 1].

Taken together, these different behavioral results indicate that SLC reduced the response conflict that only standard-incongruent trials involve. Consequently, if N_{inc} is indeed sensitive to response (or general) conflict, the stronger negativity at around 400ms elicited by standard-incongruent items compared to both color-associated and color-neutral items in the ALC condition should therefore be reduced in the SLC condition. Alternatively, if N_{inc} is

⁴ Indeed, the direct analysis of magnitudes for both standard and semantic Stroop interference (observed at each level of Coloring (see Table 1) revealed the expected orthogonal interaction [$F(1,27) = 9.07$; $p < .01$, $\eta_p^2 = .25$]. Accordingly, its decomposition showed that the standard Stroop interference of 75ms in ALC was reduced to 25ms in SLC [$F(1,27) = 8.97$; $p < .01$, $\eta_p^2 = .25$], whereas semantic Stroop interference remained statistically equivalent in both the ALC and SLC conditions [17 and 10ms respectively; $F(1,27) = 0.38$; $p = .54$, *ns*].

sensitive to semantic conflict only, the stronger negativity at around 400ms elicited by both standard-incongruent and color-associated items compared to color-neutral items should not differ as a function of coloring.

To test these competing hypotheses, mean N_{inc} amplitudes were subsequently analyzed in a Stimulus-type \times Coloring \times Location repeated-measures ANOVA. This analysis revealed significant main effects of Stimulus-type [$F(1.88, 50.87) = 9.99; p < .001, \eta_p^2 = .27$], Coloring [$F(1,27) = 6.06; p < .05, \eta_p^2 = .18$] and Location [$F(1.81, 48.87) = 4.4; p < .05, \eta_p^2 = .14$], as well as a Stimulus-type \times Location interaction [$F(3.14, 84.72) = 4.00; p < .01, \eta_p^2 = .13$].

The Stimulus-type \times Coloring interaction that would be expected if N_{inc} is sensitive to general and/or response conflict remained non-significant [$F(1.73, 46.77) = 0.57; p = .54, ns$] and was also not embedded in the overall Stimulus-type \times Coloring \times Location interaction that also remained non-significant [$F(3.40, 91.79) = 1.23; p = .31, ns$]. Moreover, the decomposition of the significant Stimulus-type \times Location interaction mentioned above suggests that the simple main effect of Stimulus-type was significant at the left [F1F3; $F(1.79, 48.24) = 14.16; p < .001, \eta_p^2 = .34$], central [Fz; $F(1.84, 49.75) = 5.49; p < .01, \eta_p^2 = .17$] and right [F2F4; $F(1.97, 53.33) = 3.94; p < .05, \eta_p^2 = .13$] locations (see Table 2).

< Table 2 >

Further comparisons revealed that differences in N_{inc} amplitude between incongruent and neutral trials were significant (all $p_s < 0.01$), as were those between color-associated and neutral trials ($p_s < 0.01$ at F1F3 and Fz and $p = .055$ at F2F4), whereas the differences in N_{inc} amplitudes between incongruent and color-associated trials were not significant at any of these locations ($p_s > 0.18$).

Even though the non-significant Stimulus-type \times Coloring and Stimulus-type \times Coloring \times Location interactions should be interpreted with caution, the aforementioned ERP

results seem to be somewhat incompatible with the idea that N_{inc} is sensitive to response and/or general conflict.

Discussion

The behavioral results reported above indicated that SLC significantly speeded up RTs for standard-incongruent trials whereas this procedure left RTs for color-associated and neutral trials unaffected. It should be remembered at this point that only standard-incongruent items (unlike their color-associated counterparts) involve a response conflict. Yet, the N_{inc} amplitudes elicited by both standard incongruent and color-associated items remained statistically equivalent. Furthermore, although the behavioral results clearly indicate that SLC reduces the response conflict, no such reduction was observed in the ERP data. Indeed, both standard-incongruent and color-associated items led to a stronger negativity than color-neutral items at around 400ms, and this result was not (unlike behavioral data) modulated by SLC. Thus, in the light of these different data, and in agreement with past studies, we are inclined to conclude that this time window is in fact sensitive to semantic conflict and/or its resolution (e.g., Coderre et al., 2011; Killikelly & Szücs, 2013; Szücs & Soltész, 2010).

Indeed, the joint consideration of behavioral and ERP results seems somewhat incompatible with the conclusions of other past studies suggesting that the Stroop-related N_{inc} is sensitive to general conflict (e.g., Hanslmayr et al., 2008) or, alternatively, to response conflict (e.g., Appelbaum et al., 2009). However, such conclusions remain tentative because the respective contributions of semantic and response conflict to overall Stroop interference were confounded in these studies (see e.g., Ferrand & Augustinova, 2014 for further details).

Given that it is still highly plausible that the N_{inc} observed in the present study reflects the mobilization of central executive processes (e.g., Hanslmayr et al., 2008), these processes

do not seem to be elicited in response to general and/or response conflict but rather in response to semantic conflict.

Even though such a conclusion might appear to be weakened by the significant main effect of Coloring reported above, it should be noted that the negativity averaged for all types of items (which it is difficult to consider as an indicator of conflict-sensitivity *per se*)⁵ was significantly greater in SLC than in ALC⁶. This would mean that SLC items lead to more conflict than ALC items and this is clearly not the case. Thus this main effect is most likely to reflect the fact that, rather like N400, N_{inc} is sensitive to variations in both linguistic (e.g. incongruency) and non-linguistic (e.g., coloring) parameters (see e.g., Kutas & Federmeier, 2011 for a discussion).

But before concluding that the N_{inc} observed in the semantic Stroop paradigm is N400-like and therefore sensitive to semantic conflict and/or its resolution, future research will be needed to replicate these results in both vocal and manual formats. Indeed, another limitation of the present study is that given the muscular and movement artifacts resulting from the use of the original vocal responses (Stroop, 1935), we were unable to explore some late components known to be sensitive to Stroop interference. Indeed, it would have been interesting to examine whether the late negativity (LN occurring 600-800ms after stimulus-onset; see e.g., Hanslmayr et al., 2008) or the late positivity complex (LPC occurring between 500 and 900ms, see e.g., Appelbaum et al., 2009) are sensitive to the semantic and/or response conflict. Given that the detection and/or resolution of response conflict is thought to arise later in the processing of standard-incongruent Stroop words (e.g., Ferrand & Augustinova, 2014), it remains plausible that these late components are indeed sensitive to

⁵ It should be recalled that N_{inc} is a relative negativity resulting from the difference between incongruent and color-neutral items.

⁶ $M_{SLC} = -1.08$, $SE_{SLC} = 0.39$ vs. $M_{ALC} = -0.77$, $SE_{ALC} = 0.34$

response conflict (see e.g., Hanslmayr et al., 2008 for Stroop-related LN results that are compatible with such idea) and thus strongly modulated by SLC.

Even though, the EEG data reported above constitute perhaps the most novel and important aspect of this study, the replication of our past behavioral findings (Augustinova & Ferrand, 2007; Augustinova et al., 2010) is also noteworthy. Indeed, despite a different implementation of SLC from both Augustinova and Ferrand (2007) and Augustinova et al. (2010), the present study showed once again that SLC reduced the response conflict (see also alternative account of Manwell et al., 2004). Thus, this pattern of results tends to contradict other current explanations of the SLC-effect (see e.g., Küper & Heil, 2012 for detailed discussion of empirical data underlying these accounts). Indeed, the fact that, in our results, SLC speeded up RTs on standard-incongruent but not on color-associated and neutral trials is clearly incompatible with both the account suggesting that SLC reduces semantic conflict (e.g., Besner et al., 1997; Manwell et al., 2004) and the one suggesting that SLC slows processing of neutral items (e.g., Küper & Heil, 2012; Monahan, 2001). However, more empirical data is needed if we are to fully explore this as yet unresolved question, namely because past studies vary in their implementations of SLC.

It is important to note that the use of SLC or other procedures that are known to reduce Stroop interference (see e.g., Augustinova & Ferrand, 2014, in press for review) is clearly of value for addressing the question of whether Stroop-related N_{inc} is sensitive to the semantic, response or both types of conflicts – the question that cannot be reliably answered without separating semantic conflict from response conflict⁷. The semantic variant used in the present study is a particularly suitable tool for such undertaking because it involves no changes to the original Stroop task (i.e., it is not a new Stroop-like task) and it is not, unlike the paradigm

⁷ The same reasoning actually applies to the use of standard-congruent items ($BLUE_{blue}$) as a baseline, because such items elicit facilitation (i.e., qualitatively different phenomenon from interference that incongruent items involve, see e.g., Brown, 2011) due respectively to semantic and response compatibility.

used in the aforementioned work by Szücs and colleagues, restricted to manual responses. Thus it is to be hoped that it will generate an additional incentive to conduct more careful behavioral and electrophysiological investigations of Stroop interference.

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Table 1. Mean correct latencies (in ms), Standard Deviations (in parentheses), and percentage error rates as a function of type of Stimulus and Coloring

	All letters colored			Single letter colored			SLC effect
	RT	95% CI	%ER	RT	95% CI	%ER	
Incongruent (I)	863 (116)	[818, 907]	4.40	818 (88)	[784, 852]	4.64	45**
Color-associated (CA)	805 (95)	[768, 842]	1.43	803 (93)	[767, 839]	2.86	2
Color-neutral (N)	788 (95)	[751, 824]	1.55	793 (98)	[754, 831]	1.90	-5
Standard Stroop Interference (I-N)	75**	[47, 104]		25**	[9, 41]		
Cohen's <i>d</i>	0.70			0.26			
Semantic Stroop Interference (CA-N)	17*	[0, 34]		10*	[0, 21]		
Cohen's <i>d</i>	0.17			0.10			
Response Interference (I-CA)	58**	[32, 84]		15*	[3, 27]		
Cohen's <i>d</i>	0.54			0.16			

* $p < .05$; ** $p < .01$; CI = confidence interval; Cohen's *d* = effect size, based on Cohen (1988).

Table 2. Mean N400 amplitudes in μV , Standard Deviations (in parentheses) as a function of type of Stimulus and Location.

	F1F3	Fz	F2F4
Incongruent (I)	-1.51 (1.93)	-1.42 (2.28)	-.66 (2.31)
Color-associated (CA)	-1.26 (1.80)	-1.36 (2.22)	-.52 (2.32)
Color-neutral (N)	-.51 (1.80)	-.88 (2.42)	-.20 (2.28)
Standard Stroop Interference (I-N)	-1.00**	-.53*	-.45*
Cohen's <i>d</i>	0.53	0.23	0.20
Semantic Stroop Interference (CA-N)	-.76**	-.48**	-.32
Cohen's <i>d</i>	0.41	0.20	0.13
Response Interference (I-CA)	-.25	-.06	-.14
Cohen's <i>d</i>	0.13	0.02	0.06

* $p \leq .05$; ** $p \leq .01$; Cohen's *d* = effect size, based on Cohen (1988).

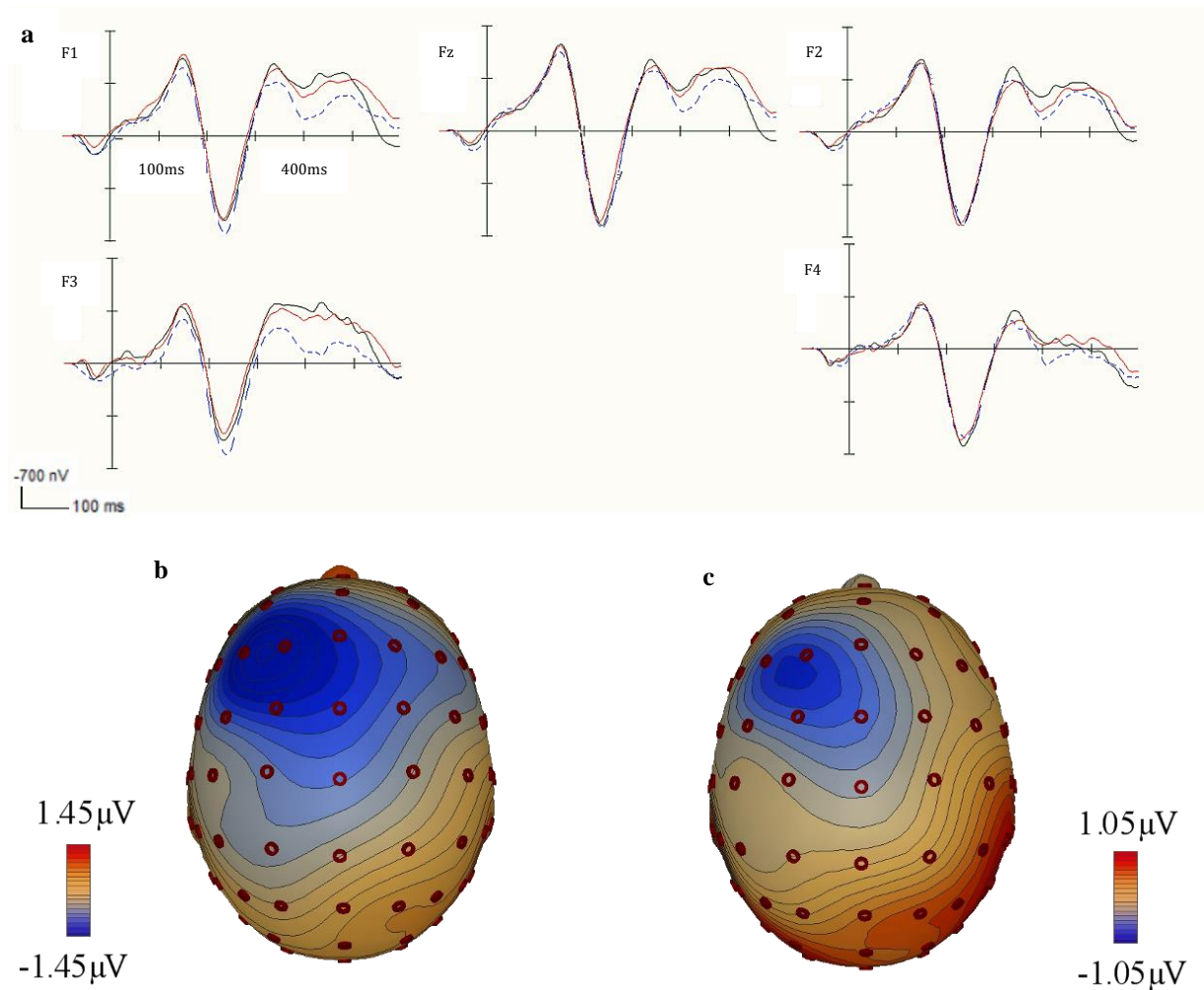


Figure 1a) N_{inc} amplitudes for incongruent (in black), color-associated (in red) and neutral trials (in blue) at left (F1,F3), central (Fz) and right (F2,F4) locations (averaged for both SLC and ALC conditions); **1b)** topography (at 430 msec) for standard and for **1c)** semantic Stroop interference.