

Research report

ERP correlates of the conflict level in the multi-response Stroop task



Adam Chuderski^{a,*}, Magdalena Senderecka^a, Patrycja Kałamała^a, Bartłomiej Kroczeek^b,
Michał Ociepka^b

^a Institute of Philosophy, Jagiellonian University in Krakow, Grodzka 52, 31-044 Krakow, Poland

^b Institute of Computer Science and Computational Mathematics, Jagiellonian University in Krakow, Łojasiewicza 6, 30-348 Krakow, Poland

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ABSTRACT

This EEG study ($N=33$) examined event-related potentials associated with conflict between activated responses in the Stroop task, in order to examine the conflict monitoring theory of cognitive control, which predicts the strength of exerted control to be proportional to the detected level of conflict. However, existing research manipulated the sole presence/absence of conflict, but not its exact level. Here, by using a modified color-word task that allowed multiple correct responses for target colors, as well as multiple incorrect responses for distractor words, we manipulated the level of conflict among activated responses (and not only its presence). We expected that a larger number of activated incorrect responses (i.e., a presumably higher conflict) would entail more pronounced conflict-related potentials. Indeed, two components of the N450 wave, parietal negativity and medial frontal negativity, were more negatively deflected when conflict was higher, than when it was lower, visibly responding to the level of conflict. Slow potential weakly responded to the sheer presence of conflict, but not to its level. These results can be plausibly explained by the conflict monitoring theory with a modified conflict evaluation formula, whereas they are at odds with several alternative theories of cognitive control.

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1. Introduction

Cognitive (or executive) control is a crucial mental faculty that allows humans to flexibly direct their thoughts and actions in order to reach adopted goals, even in the face of interfering stimulation or conflicting response tendencies (Chuderski and Nęcka, 2010). In laboratory settings, cognitive control is studied with the use of conflict tasks (also called congruency tasks). The hallmark conflict task is the Stroop (1935) task, which consists of presenting bivalent stimuli that elicit both weakly-learned (non-dominant) and strongly-learned (dominant) cognitive processes, and requires participants to process and respond to the non-dominant aspect, while ignoring the dominant one (see also MacLeod, 1991). In its standard version, participants are asked to name the ink color of a word while ignoring the meaning of the word, which itself refers to a color. The task yields commonly observed interference effects that consist of increased response latency, and often also error rate, in incongruent or conflict trials, when the color denoted by a word mismatches the ink color (e.g., word 'RED' printed in blue ink), compared to response latency/error rate in congruent or no-conflict (word and ink color match) and neutral trials (e.g., a color

of 'XXXXX' string has to be named). This interference reflects difficulty in suppressing the dominant process, as barely no interference is noticed when colored words need to be read instead (Blais and Besner, 2006).

Interference effects have also been found in several Stroop-like tasks, like responding to symbols surrounded by other symbols (the flanker task; Eriksen and Eriksen, 1974), counting numbers (Shor, 1971), indicating relative positions of words denoting positions (e.g., 'left' presented on the right side; Seymour, 1973), and categorizing large objects comprising smaller objects (Navon, 1977). All these tasks helped researchers to understand the neurocognitive mechanisms of cognitive control. Most importantly, it has been demonstrated that control can be dynamically recruited in response to detected conflicts. Such dynamic adjustments in control are termed "conflict adaptation effects". For example, interference effect decreases in trials following incongruent trials (the so-called Gratton effect; Gratton et al., 1992), or in primarily-incongruent trial sequences (the so-called proportion congruent effect; Logan and Zbrodoff, 1979; Tzelgov et al., 1992). All these observations led to the conception of the influential conflict monitoring theory (Botvinick et al., 2001), which proposes that the brain, in an on-line manner, evaluates the level of conflict between incongruent responses. Then, the conflict level is used in order to regulate the strength of control exerted over response selection,

* Corresponding author.

E-mail address: adam.chuderski@gmail.com (A. Chuderski).

with a stronger control elicited in more conflicting situations, for instance when the incongruent trials dominate the trial sequence (for a review of studies that support the conflict monitoring theory see [Niendam et al., 2012](#)). The fact that conflict is primarily related to response selection is supported by the response-set effect: Stroop interference decreases when an incongruent word denotes a color that has not been defined for the task ([Proctor, 1978](#)).

However, the manipulation with sheer response latency/error rate can in principle be accounted for with no reference to conflict monitoring. For example, it can be explained in terms of stimulus repetition and response priming ([Mayr et al., 2003](#)), learning contingencies between distractors and responses ([Melara and Algom, 2003](#); [Schmidt, 2013](#)), and Bayesian prediction of conflict to come ([Jiang et al., 2014](#); [Yu et al., 2009](#)). Thus, more specific and powerful tests of the conflict monitoring theory as well as its competitors use the brain correlates of conflict precisely located in time, that is, the electroencephalographic event-related potentials (ERPs).

A conflict-related ERP which was studied as first using the flankers was the N2 component – a substantial negative peak in neural activity that occurs between 250 and 350 ms after incongruent stimulus onset, whereas a much lesser peak is observed for congruent stimuli ([Kopp et al., 1996](#); [Yeung and Nieuwenhuis, 2009](#)). N2 is detected primarily at the fronto-central electrodes, and can be explained by dipoles located in the anterior cingulate cortex (ACC; e.g., [Van Veen and Carter, 2002](#)). However, in the classical color-word task, as compared to the flankers, usually N2 is not related to conflict ([Tillman and Wiens, 2011](#)). Instead, two other components – N450 and slow potential (SP) – have been found to be strongly linked to incongruent trials ([West and Alain, 2000](#)).

N450 is a negative peak in amplitude that occurs about 400–500 ms after stimulus onset, and is more pronounced for incongruent trials than congruent (or neutral) ones ([West and Alain, 2000](#); [West et al., 2005](#)). Like N2, N450 is usually located fronto-centrally, and recent ERP source localization studies have revealed that most variance in the topography of the N450 can be explained by dipoles also found in the ACC ([Hanslmayr et al., 2008](#); [Liotti et al., 2000](#); [Szűcs et al., 2009](#)).

EEG data on N2 and N450 are also consistent with neuroimaging experiments indicating that the ACC plays a crucial role in response conflict detection and resolution ([Cohen et al., 2000](#); [Van Veen et al., 2001](#)). Simultaneously, other fMRI studies have pointed out that the ACC can also be activated by sheer stimulus conflict, for instance when semantically incongruent word and color are both mapped onto the same response ([Weissman et al., 2003](#); [Weissman et al., 2005](#); [Van Veen and Carter, 2002](#)). These observations support the hypothesis that the ACC is involved in conflict monitoring across several information domains ([Botvinick et al., 2004](#)).

N2 and N450, although both interpreted as conflict detectors associated with the ACC, often were differently modulated by conflict. N2 (e.g. [Clayson and Larson, 2012](#)), but not N450 (e.g. [Larson et al., 2009](#)), showed the Gratton effect, while the reverse was true for the proportion-congruent effect ([Bartholow et al., 2005](#); [West and Alain, 2000](#)). However, [West et al. \(2012\)](#) suggested that in fact both N2 and N450 may index similar processes dealing with conflict-induced adjustments of cognitive control. The differences in time windows, in which the respective conflict-related ERPs are observed, may simply result from the differences in processing demands of various conflict tasks. For instance, the flankers involve little semantic interference, so the (motor) conflict may occur faster than does the conflict in the Stroop, which requires also semantic processing (see [Pires et al. \(2014\)](#)). Moreover, [West et al.](#) showed N450 to combine two distinct conflict-sensitive modulations: one observed in the fronto-central midline region

(named the “medial frontal negativity”, MFN), and the other pronounced in the parietal electrodes (named the “parietal negativity”, PN). Only MFN responded reliably to the Gratton effect (in the counting Stroop task), whereas PN did not. It was suggested that MFN reflects the between-trial control adjustments, whereas PN indexes the within-trial conflict resolution and control modulation. According to [West et al.](#), previous studies might have missed MFN’s sensitivity to the Gratton effect due to averaging MFN and PN components.

Slow potential (SP) starts about 500 ms after stimulus onset, and is sustained until response is made ([West and Alain, 2000](#)). SP is more positive for incongruent than congruent trials. Source analysis of the SP have revealed neural generators within the middle or inferior frontal gyrus and the left extrastriate region ([West, 2003](#)). The activity of lateral frontal and posterior cortices may reflect the recruitment and engagement of control mechanisms which are needed to resolve interference among potential responses ([West and Alain, 2000](#)), and/or to select the proper response ([West et al., 2005](#)). The location of the dipole identified by [West \(2003\)](#) in the left extrastriate cortex has appeared relatively close to activations observed in some fMRI studies of the Stroop task (e.g., [Banich et al., 2000](#)). SP clearly responds to the conflict adaptation effects, like the Gratton effect ([West et al., 2012](#)) and the proportion congruent effect ([Larson et al., 2009](#)). As SP increases with latency and accuracy of responses, it is interpreted as an index of conflict resolution (not conflict detection) that leads to response selection ([West et al., 2005, 2012](#); for reviews on both N450 and SP see [Larson et al., 2014](#); [Pires et al., 2014](#)).

However, the presence of specific ERPs in the conflict trials was described in other terms than in terms of conflict detection/monitoring. For example, the N2 wave was supposed to reflect the reinforcement learning of error/risk likelihood ([Brown and Braver, 2007](#); [Holroyd and Coles, 2002](#)), the discrepancy between predicted and occurred response outcomes ([Alexander and Brown, 2011](#)), or even just the time spent on task, with more time needed for incongruent than for congruent trials ([Grinband et al., 2011](#); but see [Yeung et al. \(2011\)](#)).

One way of testing these presumed alternative mechanisms of conflict-related ERPs is the precise comparison of discrepant predictions of computational models implementing particular mechanisms. [Yeung and Nieuwenhuis \(2009\)](#) demonstrated that when the conflict monitoring model/the reinforcement learning model yielded a contrasting prediction regarding the more/less pronounced N2 in the slow flanker trials, as compared to the fast trials, the data did not support the latter model. However, [Alexander and Brown \(2011\)](#) showed that the former prediction (and several others) can easily be handled by their predicted response-outcome model.

Another way to test the conflict monitoring account of N2/MFN/PN/SP is to manipulate the amount of conflict in the task, beyond the sheer presence/absence of conflict. Such manipulations, so far, relied on the two-to-one stimulus-response (S-R) mappings, that is, two stimuli are associated with one and the same response (see [Kornblum et al., 1990](#)). For example, [Chen et al. \(2011\)](#) found that the MFN amplitude was more pronounced in the color-word task when the conflict pertained both to stimulus (the meaning of a word mismatched its color) and response (the word and its color activated distinct responses) than when it pertained only to stimulus (the word and its color mismatched, but activated the same response). Still, however, the latter case yielded a larger MFN amplitude than the (fully) congruent condition (but see [Van Veen and Carter \(2002\)](#)). Thus, the amount of conflict in the conflicting trials (either conflict present solely between stimuli, or conflict present between both stimuli and response options) correlated with the respective conflict-induced ERPs, in line with existing computational models (e.g., [Davelaar, 2008](#)).

In this paper, we adopted another method of continuous manipulation of the conflict level in the Stroop task. Specifically, apart from the one-to-one, we used the one-to-two and one-to-three S-R mappings, for which we required people to respond with a random button drawn from either two or three eligible buttons associated with one and the same stimulus. This kind of situation, as far as we know, has never been examined in the context of laboratory tests of executive control. To date, EEG studies on conflict pertained to situations in which in a given conflict trial two responses were possible, and one led to a different outcome than did the other (e.g., pressing one button for a color, and another button – for a word). In consequence, the conflict monitoring theory adopted a conflict level quantification, originating in “degree-of-conflict” metric proposed by Berlyne (1960), which assumes that conflict exists among a set of mutually incongruent response options. Its level is proportional to their number as well as to the equipotentiality of their activation (for a given number of response options, the largest conflict will occur when all response options yield identical activation). In the case of conflict between two responses, Botvinick et al. (2001) implemented in their conflict-monitoring network a particular variant of the Berlyne metric, called Hopfield energy, which equals $E = -\sum w_{ij} a_i a_j$, where: a denotes activation of competing responses i and j (output nodes of the network), w_{ij} is a negative connection weight between them (reflecting their competition), and summation applies to all possible pairs of responses. Assuming two alternative responses with w equaling -1 , the conflict level simply depends on $a_1 a_2$. In congruent trials (two stimuli activate the same response), only one output node gained high positive activation (let us say: 1), while the other node's activation was close to 0, so E was close to 0. In incongruent trials (two responses are activated), both nodes were highly active (both equal to 1), so E was also high (i.e., equaled 1). By using value E to strengthen task-relevant responses, the Botvinick et al. model replicated several conflict adaptation effects, like the proportion-congruent and Gratton effects.

However, in real life, the case that each response option conflicts with any other option is unusual. Commonly, multiple actions are possible to achieve one and the same outcome (e.g., stopping a bike with the front or rear break, or meeting friends at pub or on Skype). Hopfield energy, in the form implemented by Botvinick et al., does not provide an adequate assessment of the conflict level when some subsets of potential responses are mutually congruent. For example, when the above two alternative response options are supplemented with another response option congruent with one of them (i.e., both weighted 1), but incongruent with the other one (i.e., both weighted -1), value E will be insensitive to this change, as it will still equal 1 (i.e., $-[-1 \times 1 - 1 \times 1 + 1 \times 1]$). Simply, the additional conflict between the incongruent and the new response option will be counterbalanced by the decrease in conflict due to the congruency between the congruent and the new response option. This is at odds with a rational assumption that the conflict level should change when an additional response option is introduced, because another in/congruent response increases likelihood of an in/correct response, so the respective situation becomes more/less conflicting.

In order to account for the above situation (not handled by the Berlyne quantification), another conflict metric was proposed by Festinger (1957) and Festinger and Carlsmith (1959). It quantifies the conflict level as a (weighted) ratio of the number of incongruent response options (incongruent with regard to a predefined correct goal-relevant response) to the number of all responses allowed in a certain situation. So, when X represents the number of incongruent response options, and Y reflects the number of response options congruent with the goal-relevant response (including this very response), according to Festinger the conflict level will be proportional to $X/(X+Y)$. It is easy to see that the

conflict level quantified in this way will change from the above two-response conflict case (conflict equaling about $\frac{1}{2}$) to the three-response case with two mutually congruent response options (conflict equaling about $\frac{1}{3}$ or about $\frac{2}{3}$, depending on whether the latter options constitute the target outcome or not). In the context of our multi-response Stroop task with the one-to-one, one-to-two, and one-to-three S-R mappings, for a given mapping of the target stimulus (e.g. two responses mapped to a color), the number of possible but incorrect responses to a distractor stimulus can vary (i.e., be either one or three responses mapped to a color named by a word). If the Festinger formula is right, then for a higher number of incorrect response options the amplitude of conflict-related ERPs should be more pronounced, comparing to the ERP amplitude for a lower number of incorrect response options.

To test this prediction, we applied a Stroop task in which for each particular target color (out of three colors used in the task) either one, two, or three correct responses (buttons) were defined (the eligible responses factor). These colors were combined with words that named the very same set of colors, thus they primed either one, two, or three buttons (a particular combination of target-distractor buttons is henceforth denoted by a corresponding X-Y symbol, for example 2-3 denotes a color associated with two buttons-a word naming a color associated with three buttons). For each consecutive **number** of eligible responses to a color, the three levels of the conflict factor were defined: no conflict (no incongruent responses – words prime the same (*number* of) buttons as do colors; conditions 1-1, 2-2, and 3-3), low conflict (words prime a relatively lower *number* of incongruent buttons; conditions 1-2, 2-1, 3-1), or high conflict (words prime a relatively higher *number* of incongruent buttons; conditions 1-3, 2-3, 3-2). In consequence, for each level of eligible responses, the low versus high conflict trials yielded lower versus higher value of the Festinger formula: $2/[1+2]$ (66%) versus $3/[1+3]$ (75%) for one eligible response, $1/[2+1]$ (33%) versus $3/[2+3]$ (60%) for two eligible responses, and $1/[3+1]$ (25%) versus $2/[3+2]$ (40%) for three eligible responses, respectively (note that mean conflict across eligible responses was 41% in the low-conflict trials versus 58% in the high conflict trials). We expected that, for a given level of eligible responses, the observed amplitudes of PN, MFN, and SP would be more pronounced in the high-conflict trials than in the low-conflict trials. We also analyzed whether any significant effects of the conflict level would differ between the left, midline, and right clusters of electrodes.

2. Results

2.1. Behavioral data

Mean reaction times (RT) and mean error rate (ERR) were compared across the conditions of the task. Only correct trials (95%) were taken into consideration in the RT analyses. In order to control for outliers, trials on which RT was more than 2.5 median absolute deviations (MAD) above or below the median RT were excluded from the behavioral analysis (5% of trials). The RT data was normally distributed as indicated by the Kolmogorov-Smirnov test ($d=0.15$, $p > 0.20$).

The 3×3 ANOVA of RT data (see Table 1) yielded a significant effect of eligible responses, $F(2, 64)=6.41$, $p < 0.001$, $\eta^2=0.17$, which reflected Hick's (1952) Law, and indicated the significant increase in RT between one ($M=663$ ms) and two responses ($M=696$ ms), $F(1, 32)=12.00$, $p < 0.001$, $d=0.24$, but not between two and three ($M=692$ ms), $F < 1$. ANOVA yielded also a significant effect of the conflict level, $F(2, 64)=24.83$, $p < 0.001$, $\eta^2=0.44$, showing the increase between the mean RT in the no-conflict ($M=650$ ms) and the mean RT in the low- ($M=700$ ms) and high-

Table 1

Mean response latency in all conditions of the multi-response Stroop Task (With SD). Conditions are indexed by the number of eligible responses per target-distractor.

| No. of responses | | No conflict | Low conflict | High conflict |
|------------------|-----------|-------------|--------------|---------------|
| One | Condition | 1-1 | 1-2 | 1-3 |
| | Latency | 631 (149) | 677 (167) | 681 (168) |
| Two | Condition | 2-2 | 2-1 | 2-3 |
| | Latency | 664 (164) | 718 (192) | 707 (179) |
| Three | Condition | 3-3 | 3-1 | 3-2 |
| | Latency | 659 (160) | 706 (177) | 713 (188) |

Table 2

Mean error rates in all conditions of the multi-response Stroop Task (With SD). Conditions are indexed by the number of eligible responses per target-distractor.

| No. of responses | | No conflict | Low conflict | High conflict |
|------------------|------------|---------------|---------------|---------------|
| One | Condition | 1-1 | 1-2 | 1-3 |
| | Error Rate | 0.037 (0.030) | 0.068 (0.067) | 0.067 (0.067) |
| Two | Condition | 2-2 | 2-1 | 2-3 |
| | Error Rate | 0.049 (0.043) | 0.067 (0.062) | 0.075 (0.068) |
| Three | Condition | 3-3 | 3-1 | 3-2 |
| | Error Rate | 0.031 (0.034) | 0.044 (0.043) | 0.047 (0.046) |

conflict conditions ($M=700$ ms), $F(1, 32)=31.33$, $p < 0.001$, $d=0.38$, but not between the two latter conditions, $F < 1$. No significant interaction between the two investigated factors was found, $F < 1$.

The 3×3 ANOVA of ERR (see Table 2) revealed a significant effect of eligible responses, $F(2, 64)=6.98$, $p < 0.001$, $\eta^2=0.18$, and indicated the significant difference in ERR between two ($M=0.064$) and three responses ($M=0.040$), $F(1, 32)=13.22$, $p < 0.001$, $d=0.60$, but not between one ($M=0.057$) and two responses, $F(1, 32)=1.43$, $p=0.24$. ANOVA yielded also a significant effect of the conflict level, $F(2, 64)=8.73$, $p < 0.001$, $\eta^2=0.21$, showing the increase in the ERR between the no-conflict ($M=0.039$) and the low- ($M=0.060$) and high-conflict conditions

($M=0.063$), $F(1, 32)=12.55$, $p < 0.001$, $d=0.53$, but not between the two latter conditions, $F < 1$. No significant interaction between the two investigated factors in the ERR was found, $F < 1$.

2.2. EEG data

Fig. 1 presents the grand average ERPs to the stimulus at representative sites. Scalp distribution maps for the three difference waves (the contrasts between the low- minus no-conflict condition, the high- minus no-conflict condition, and the high- minus low-conflict condition) are shown in Fig. 2.

2.2.1. Parietal negativity

For PN, the 3×3 ANOVA of the conflict level and eligible responses factors yielded the main effect of the conflict level (for this and two other components, the results of statistical tests pertaining to are presented in Table 3), which indicated the significant contrast between the high- ($M=4.09 \mu\text{V}$) and low-conflict condition ($M=4.60 \mu\text{V}$), as well as between the high- and no-conflict condition ($M=4.84 \mu\text{V}$). The contrast between the no- and low-conflict condition was not significant. There was no significant main effect of eligible responses. Furthermore, the factors yielded no significant interaction. Regarding the interaction of the conflict level with the cluster factor, when the latter was entered into ANOVA as a third factor, it was weak but significant, and it indicated a significantly larger negative difference in amplitude between the high- and low-conflict conditions in the right cluster ($\Delta M=-0.75 \mu\text{V}$), in comparison to the left cluster ($\Delta M=-0.34 \mu\text{V}$) (no significant contrast pertained to the midline cluster, $\Delta M=-0.42 \mu\text{V}$). The former difference was the only one significant.

The 2×2 ANOVA, in which the low- and high-conflict trials were collapsed into one type of (conflict) trials, and which included the current and the preceding type of trials as two factors (each having two levels: conflict vs. no-conflict trials), matched the above analysis. It yielded a significant main effect of the conflict in the current trial, but no significant (nor even marginal) main effect of the conflict in the preceding trial, nor any interactive effect. This fact means that there was no Gratton effect for PN (for

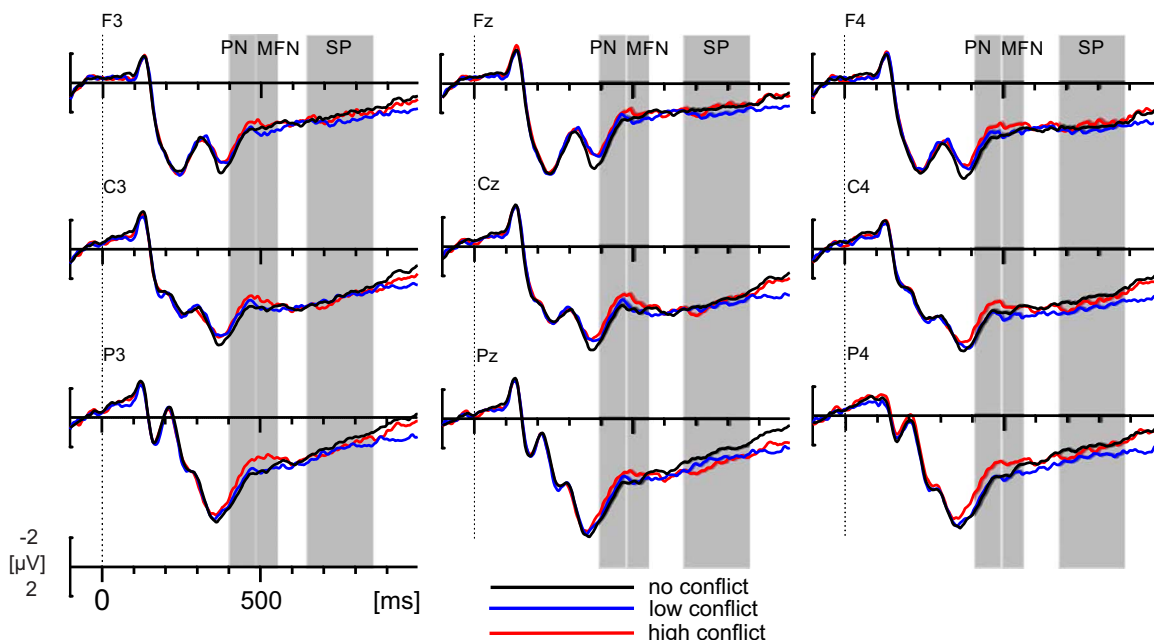


Fig. 1. Grand average (calculated over all of 33 participants) stimulus-locked ERP waveforms for the high conflict, low conflict and no-conflict conditions. Black lines mark the no-conflict condition, blue lines mark the low conflict condition, red lines mark the high conflict condition for the frontal (F3, Fz, F4), central (C3, Cz, C4) and parietal (P3, Pz, P4) electrodes. The examined intervals, reflecting the PN (400–480 ms), MFN (480–540 ms) and SP (650–850 ms) components, are highlighted.

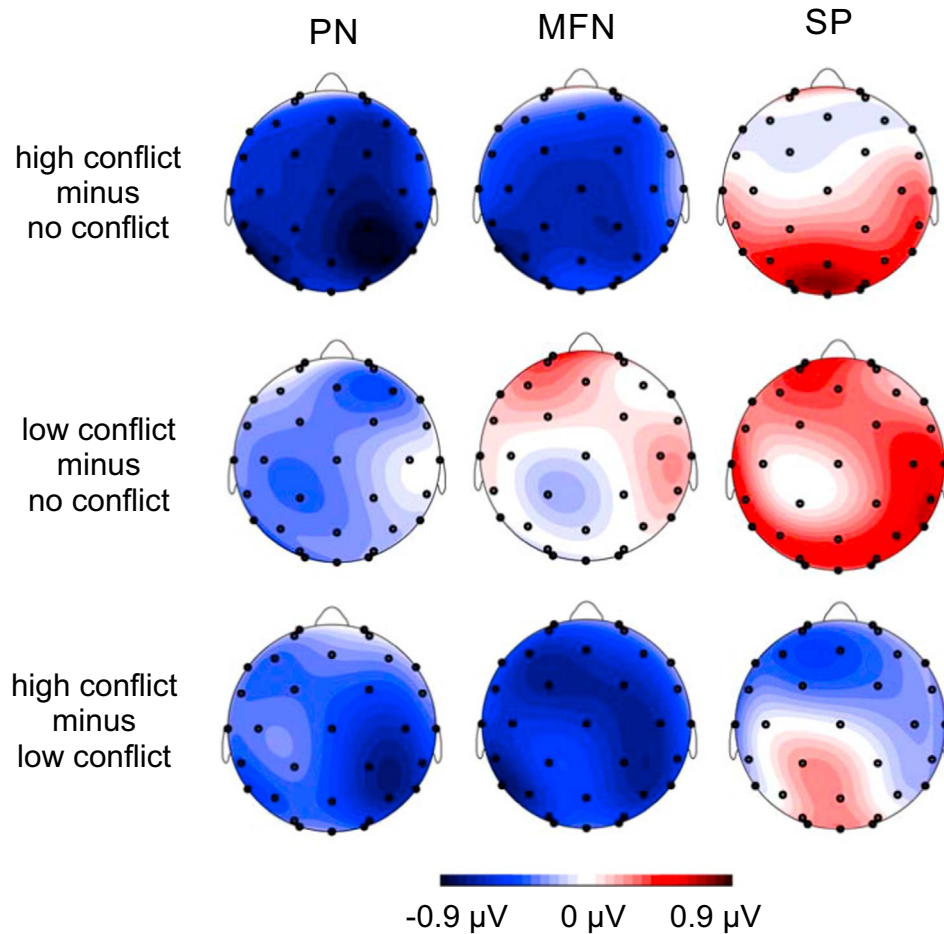


Fig. 2. Scalp topography of ERP components (averaged over all of 33 participants) for the high conflict minus no-conflict condition, the low conflict minus no-conflict condition, and the high conflict minus low conflict conditions. Left topographical plot shows the scalp distribution of the PN component (400–480 ms). Middle topographical plot shows the scalp distribution of the MFN component (480–540 ms). Right topographical plot shows the scalp distribution of the SP component (650–850 ms).

Table 3

The summary of *F*-values, *p*-values, and effect sizes for the main effect, two interactions, and all analyzed contrasts pertaining to the conflict level.

| Component | | Parietal Negativity | | | Medial Frontal Negativity | | | Slow Potential | | |
|---------------------------------|-----------|---------------------|--------------|-------------|---------------------------|--------------|-------------|----------------|--------------|-------------|
| Effects | <i>df</i> | <i>F</i> | <i>p</i> | Effect size | <i>F</i> | <i>p</i> | Effect size | <i>F</i> | <i>p</i> | Effect size |
| Conflict level (CL) main effect | 2, 64 | 5.42 | 0.007 | 0.14 | 3.32 | 0.042 | 0.09 | 2.62 | 0.080 | 0.08 |
| High (HC) vs. Low conflict (LC) | 1, 32 | 5.20 | 0.029 | 0.17 | 4.39 | 0.044 | 0.17 | 0.06 | | |
| High (HC) vs. No-conflict (NC) | 1, 32 | 8.88 | 0.005 | 0.26 | 7.32 | 0.011 | 0.15 | 3.79 | 0.060 | 0.21 |
| Low (LC) vs. No-conflict (NC) | 1, 32 | 1.15 | | | 0.18 | | | 4.76 | 0.037 | 0.20 |
| CL × electrode cluster (EC) | 4, 128 | 2.49 | 0.046 | 0.07 | 0.27 | | | 0.58 | | |
| LC vs. HC for the left EC | 1, 32 | 2.36 | | | 4.83 | 0.035 | 0.18 | 0.07 | | |
| LC vs. HC for the midline EC | 1, 32 | 2.00 | | | 2.28 | | | 0.51 | | |
| LC vs. HC for the right EC | 1, 32 | 12.27 | 0.001 | 0.24 | 5.12 | 0.031 | 0.17 | 0.01 | | |
| CL × No. of eligible responses | 4, 128 | 0.84 | | | 0.27 | | | 2.03 | 0.094 | 0.06 |

Note. *P*-values and effect sizes are shown only for significant ($p < 0.05$) and marginal effects ($p < 0.10$). Significant effects are highlighted in bold font. Effect size = η^2 for the main and interactive effects, and Cohen's *d* for contrasts.

the results of statistical tests pertaining to the Gratton effect see Table 4). No three-way interaction was found regarding the cluster factor, either.

2.2.2. Medial frontal negativity

Also in the case of MFN, the 3×3 ANOVA (see Table 3) yielded the significant effect of the conflict level. The effect of conflict was driven by the significant contrast between the low- ($M = 3.45 \mu V$) and high-conflict condition ($M = 2.84 \mu V$), as well as a similar contrast between the high- and no-conflict condition ($M = 3.33 \mu V$). The contrast between the no- and low-conflict

condition was not significant. The factor of eligible responses did not yield a significant effect, nor did it produce a significant interaction with the conflict level. When the cluster factor was entered into ANOVA, there was no significant interaction of this factor and the conflict level. That fact indicated that for MFN neither the main effect of conflict nor the high vs. low-conflict contrast was lateralized (the contrast was significant for both the left and the right cluster).

However, in contrast to PN, for MFN the 2×2 ANOVA of the conflict in the preceding and current trial showed the Gratton effect, as indicated by the almost significant interaction between

Table 4
The summary of F-values, p-values, and effect sizes for the effect of the no-conflict (NC) vs. conflict (C; averaged low- and high-conflict) preceding trials on the difference between the C and NC current trials (i.e., the Gratton effect).

| Component | Effects | df | Parietal Negativity | | | Medial Frontal Negativity | | | Slow Potential | | |
|---|---------|-------|---------------------|--------------|-------------|---------------------------|-------|----------|----------------|--------------|-------------|
| | | | F | p | η^2 | F | p | η^2 | F | p | η^2 |
| NC vs. C in current trials | | 1, 32 | 5.78 | 0.022 | 0.15 | 0.78* | | | 6.40 | 0.017 | 0.17 |
| NC vs. C in preceding trials | | 1, 32 | 0.26 | | | 0.24 | | | 2.65 | | |
| NC vs. C in current \times preceding trials | | 1, 32 | 0.05 | | | 3.91 | 0.057 | 0.11 | 0.07 | | |
| NC vs. C in current \times preceding trials \times electrode cluster (EC) | | 2, 64 | 2.04 | | | 1.43 | | | 0.38 | | |

Note. p-Values and effect sizes are shown only for significant ($p < 0.05$) and marginal effects ($p < 0.10$). Significant effects are highlighted in bold font.

* Related to significant current \times preceding trials interaction, the NC vs. C difference was significant in the current trials preceded by C trials, $F(1, 32) = 4.70$, $p = 0.038$, $d = 0.13$, but not in those preceded by NC trials, $F(1, 32) = 0.29$.

the two factors (see Table 4). This interaction indicated a larger negative difference in amplitude ($\Delta M = -0.45 \mu V$) between the conflict ($M = 3.07 \mu V$) and no-conflict trials ($M = 3.52 \mu V$) following the conflict trials, than was the respective difference ($\Delta M = 0.13 \mu V$) in trials following the no-conflict trials ($M = 3.25 \mu V$, $M = 3.12 \mu V$, for the conflict and no-conflict trials, respectively). There was no significant three-way interaction when the cluster factor was entered, what indicated that the Gratton effect for MFN was not visibly lateralized.

2.2.3. Slow potential

For SP, the 3×3 ANOVA (see Table 3) yielded only a significant main effect of eligible responses, which indicated a larger amplitude for the two-response condition ($M = 2.01 \mu V$) than for the one-response condition ($M = 1.28 \mu V$), $F(1, 32) = 6.55$, $p = 0.015$, $d = 0.28$. No significant contrast pertained to the three-response condition ($M = 1.44 \mu V$). The influence of the conflict level was not significant. Only the contrast between the no- ($M = 1.24 \mu V$) and low-conflict ($M = 1.72 \mu V$) reached significance, and the one between the no- and high-conflict ($M = 1.78 \mu V$) approached it. There was no significant contrast between the low- vs. high-conflict condition. The conflict level factor became significant in the 2×2 ANOVA, however, no interaction (Gratton effect) with the preceding versus the current trials was found (see Table 4). A similar difference in amplitude between the conflict and no-conflict trials was present in SP after no-conflict trials ($\Delta M = 0.49 \mu V$), as after conflict trials ($\Delta M = 0.37 \mu V$). The conflict effect in the current trials was not lateralized (no interaction with the cluster factor).

3. Discussion

In this study, we manipulated the conflict level that existed between the color and the word in the color-word task, by varying the color-response mappings. With one, two, or three eligible responses for a particular color, in incongruent trials a word activated either the lower or the higher number of incorrect responses (e.g., either the 2-1 or 2-3 condition for the one-to-two S-R mapping), what corresponded to either the lower or the higher conflict level, respectively. In the behavioral data, we observed a shorter mean RT for one response option than for two and three response options, but no differences in the mean RT between two and three response options. The mean RT was also longer in the low and high-conflict conditions as compared to the no-conflict condition. However, there was no difference in the mean RT between low- and high conflict conditions.

In the EEG data, our main prediction, rooted in the conflict monitoring theory (Botvinick et al., 2001), held that the amplitude of each of the three ERP components (PN, MFN, and SP), which are commonly associated with the detection and resolution of conflicts between stimuli/responses, will be affected not only by the

very presence of conflict (i.e., conflict vs. no conflict), as to date shown by the plethora of studies, but also by the level of that conflict (i.e., high vs. low conflict). In line with our predictions, PN and MFN were more pronounced when conflict was higher, than when it was lower. In contrast, SP (weakly) responded to the sheer presence of conflict, but not to its level.

Before we start discussing the main prediction in more detail, we note that the way we identified the PN and MFN components brought results generally consistent with the West et al. (2012) study, who initially proposed such a way of defining the two components. PN (the early part of N450) was defined as a negative deflection in the centro-parietal electrodes, occurring just before the peak of the N450 wave. Exactly as West et al., we found that PN was sensitive to the presence of conflict, but was not modulated by the conflict in the preceding trial (i.e., it shows no Gratton effect). MFN (the late part of N450) was defined as the post-peak negative deflection in the fronto-central electrodes. In line with West, we found that MFN not only responded to the presence of conflict, but also displayed the Gratton effect (note that, unlike in West et al., MFN did so even in the absence of direct repetitions of target stimuli). Thus, our study supports West et al.'s claim that PN and MFN reflect somewhat different cognitive processes, and only MFN is related to the between-trial adaptation of control.

3.1. Evidence for the conflict-level effects

Most importantly, indeed the PN and MFN components, but not the SP component, were sensitive to the magnitude of conflict yielded by the incongruent trials. Both components were significantly more negatively deflected when the conflict level was high, in comparison to when it was low. The conflict level effect did not interact with the number of eligible responses ($F_s < 1$), meaning that this effect was reliable across the three conditions of responding (i.e., one, two, or three eligible responses for a target color). The effect size estimates oscillated around 0.20, suggesting that the effect was relatively weak (see Section 3.2).

The difference in PN amplitude between the high- and low-conflict conditions, found over the centro-parietal region, was especially pronounced in the right hemisphere, indicating the special responsiveness of a right lateralized neural system to the presence of multiple-response conflict. This observation is in line with the findings of previous research (West and Alain, 1999), suggesting that the left parietal region may even be suppressed when color and word information activate competing conceptual level representation. In contrast, we found no lateralization for MFN.

It is difficult to plausibly interpret the lack of significant contrast between the no- and low-conflict trials in mean voltage, for both PN and MFN. The stimuli in the latter trials definitely constituted the typical incongruent visual images of the Stroop paradigm, with the word yielding a meaning that was different

from the color it bore. Expectedly, those stimuli resulted in responses prolonged by 78 ms, in comparison to the congruent stimuli. However, a closer look at the non-significant contrast for PN shows that there was a numerical voltage deflection of 0.24 μ V in the correct (i.e., negative) direction, which in the left cluster reached even 0.33 μ V. Thus, one plausible explanation of insignificant contrasts between the no- and low-conflict condition assumes that when distractors activated a substantially lesser number of responses than were activated by targets, the resulting conflict in the brain was so moderate (see Section 3.2), that it would require a sufficient power in order to be detected (and beyond $N=33$ examined in the present study).

SP was defined as the slow increase in activation preceding the response (i.e., as the 650–850 ms interval in our study), located over the parietal electrodes. Here, SP very weakly responded to the presence of conflict, and, unlike in West et al. (2012), it was not modulated by the conflict in the preceding trial (i.e., it showed no Gratton effect). Additionally, SP, as the only component examined, was affected by the number of eligible responses. This fact supports West et al.'s conclusion that SP may reflect some processes related to response selection and/or execution.

In contrast to the effect of conflict level found in EEG data, there was no significant contrast between the low- and high-conflict trials regarding RTs. One could raise a doubt whether the high-conflict trials were in fact more conflicting, and could seek for other interpretations of the voltage effect than the one referring to conflict. However, first, it is likely that increased conflict resulted only in an increased effort of the brain to cope with that conflict (as evidenced by pronounced PN/MFN), and not with a prolonged processing of a more conflicting stimulus. To support this hypothesis, we compared the peak latency of the N450 component between the low- and high-conflict trials, and we found no significant difference (max $\Delta M=10$ ms). Second, even if high-conflict prolonged processing of a stimulus, later in processing there could appear some slack phase, like response preparation process hypothetically tapped by SP, that absorbed the shorter processing of low conflict.

On the theoretical grounds, the substantial effect of increased conflict level on the brain activation in the 400–540 ms post-stimulus window, observed in the present study, can be explained naturally by the conflict monitoring theory. The conflict level evaluation is best expressed as the (possibly, weighted) proportion of the number of incorrect responses to the total number of (both correct and incorrect) responses that are possible in a given situation. In contrast, the above effect seems to be problematic for alternative theories of cognitive control and its brain correlates. For instance, the difference in PN/MFN amplitude cannot be yielded by a larger error/risk likelihood in the trials activating a larger number of incorrect responses (see Brown and Braver (2007)), because there was no significant difference in error rate between the low- and high-conflict condition. This difference unlikely indexes the longer time spent on task in the high-conflict condition (see Alexander and Brown (2011), Grinband et al. (2011)), because there was no significant difference in RT between the low- and high-conflict conditions. The difference cannot be hypothetically explained in terms of stimulus repetition (Mayr et al., 2003), because the direct repetitions of stimuli were generally excluded from the stimuli sequence. Neither can it be explained in terms of the contingency between targets and distractors (Melara and Algom, 2003; Schmidt, 2013), which in principle are perfectly correlated in the congruent trials (the same word always matches a given color), but imperfectly – in the incongruent trials (more words can accompany a given color), because in both the low- and high-conflict trials the color-word correlation was exactly the same (50%: two distractor words were possible per color).

3.2. Limitations

One limitation of the current study is related to the fact that two out of the three low-conflict conditions (i.e., 1-2, and 2-1) required the intra-manual conflict (the target and distractor activated fingers of one and the same hand), while all of the high-conflict conditions required the inter-manual conflict (the target and distractor activated two hands). Although the present design does not allow to bypass this limitation, we do not consider this confound particularly harmful for the results. One might expect that the intra-manual conflict would be in fact larger than the inter-manual one, because in the former case activating different responses within the same effector (hand) would yield more motor cross-talk, than activating responses in disjoint hands. Yet, the observed conflict effects were opposite: the low-conflict conditions yielded decreased indexes of conflict than did the high-conflict conditions. Thus, even if our data were affected by the intra/inter-manual effects, these effects acted contra our hypotheses, so the results observed by us cannot be explained in terms of these effects.

Another limitation of the study is the fact that using two conflict conditions, and the need to apply a substantial number of trials per condition in order to obtain reliable measurements of ERPs, at the same time keeping the task relatively short, resulted in a larger proportion of incongruent trials (55.5%) than was the proportion of congruent trials (44.5%). As the proportion of congruent trials is known to positively affect the latencies and error rates of incongruent trials (Kane and Engle, 2003; Tzelgov et al., 1992), as well as the respective EEG amplitudes (West and Alain, 2000), the conflict effects observed in the present study might be attenuated, in comparison to a study which would apply more congruent than incongruent trials. Such a possible attenuation may explain the lack of significant contrasts between the no- and low-conflict trials, as well as the generally low effect sizes for significant contrast between the low- and high-conflict trials.

Finally, we tested only healthy, young adults, so our findings cannot be easily generalized onto other subpopulations, like children, aged people, or participants with attentional deficits (e.g., ADHD). Overall, in our view, all above limitations critically undermine neither the general pattern of results observed nor their interpretation. However, they suggest that those interpretations should be made cautiously, and more data from the future studies (including experiments using other response patterns, different proportions of in/congruent stimuli, as well as examining larger/more diverse samples) is needed before we can satisfactorily understand the relationship between the nature of conflicting stimuli and the brain responses to them.

3.3. Conclusion

The present study is so far the first one to demonstrate that the brain's frontal and central activity is sensitive not only to conflict between particular actions (what has already been shown in the myriad of studies), but it is also affected by the specific number of actions that lead to the incongruent outcome. In other words, the brain's activity is modulated by the exact level of conflict existing among response options, and not only by the very presence of conflict. This result can be explained in a plausible way on the grounds of the conflict monitoring theory of cognitive control, at least when the Festinger conflict evaluation formula is adopted, but is at odds with several alternative theories. The study also supports existing studies suggesting that the early (PN) versus the late (MFN) parts of the N450 wave, which is commonly associated with conflict detection/resolution in the ACC, may reflect two different cognitive processes. PN may primarily signal the within-trial detection of conflict (and – as the present study shows – its

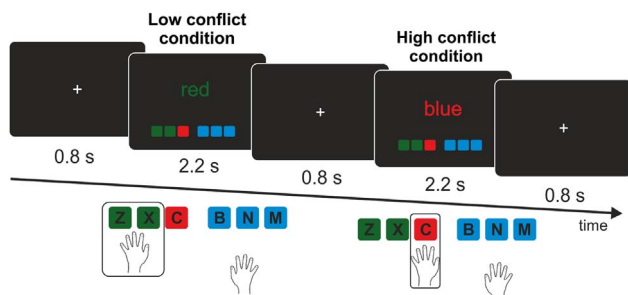


Fig. 3. The illustration of stimuli sequence in the multi-response Stroop task. In the example low-conflict trial, the target is green color, which is associated with two correct response buttons, and the distractor word “red” is associated with just one incorrect response button. The matching high-conflict trial would be the green-colored word “blue”, which would be associated with as many as three incorrect response buttons. In the example high-conflict trial, the target red color is associated with one correct response button, whereas the distractor word “blue” is associated with as many as three incorrect response buttons. The matching low-conflict trial would be the red-colored word “green”, which would be associated with two incorrect response buttons. The no-conflict trials (not depicted in the figure) were congruent colors and words, which were both associated with the same set of response buttons.

magnitude), and thus is insensitive to the Gratton effect. MFN may mainly display the between-trial adaptation to conflict (and – probably – to its magnitude), and yields the Gratton.

4. Experimental procedure

4.1. Participants

Volunteer healthy young adult participants were recruited via publicly accessible social networking websites. Each participant provided informed consent and was paid the equivalent of 8 euro in Polish zloty. A total of 33 people participated (16 women). The mean age was 22 years ($SD=3.24$, range 19–33). All participants had normal or corrected-to-normal vision. One additional person was excluded from the study because he did not understand the instruction of the Stroop task and, thus, failed to complete the task.

4.2. Procedure

The experimental procedure was carried out in accordance with the ethical principles of the 1964 Declaration of Helsinki (World Medical Organization, 1996). Participants were seated in a softly lit, sound-attenuated, air-conditioned testing room. After providing written informed consent to participate in the study, they completed three experimental tasks, with the order of tasks balanced across participants (here, only data from the multi-Stroop task are presented; two other tests were the stop-signal task and the insight problem solving task). The Stroop task lasted around 30 min, and the whole procedure (including Stroop) lasted about 2 h. Participants were asked to restrict body movements and blinking as much as possible during the recording of the EEG.

4.3. The multiple-response Stroop task

In the multiple-response Stroop task, each stimulus was drawn from three capital Polish words (approx. 7 cm × 2 cm in size) that could be printed in blue, green, or red ink, and named the colors blue, green, or red (“NIEBIESKI”, “ZIELONY”, or “CZERWONY”). Participants responded with six response buttons, with three fingers of each hand (‘Z’, ‘X’, ‘C’ / ‘B’, ‘N’, ‘M’). One color was associated with one possible button, the second – with two alternative

buttons (a participant could use any of them to respond), and the third – with three alternative buttons (each could be used to respond). Always, the 1- and 2-button stimuli were mapped to one hand, while the 3-button stimuli were mapped to the other hand, in order to avoid switching between hands when selecting the response for a stimulus. There could be four specific S-R configurations: 1-2-2/3-3-3, 2-2-1/3-3-3, 3-3-3/1-2-2, 3-3-3/2-2-1 (digits 1, 2, and 3 indicate the 1-, 2-, and 3-button stimuli), for the left-middle-right finger of the left/right hand, respectively. A particular S-R configuration out of four, and a particular assignment of colors to buttons, were randomized with replacement separately for each participant.

The sequence of stimuli was always fully random, with a constraint that the direct repetitions of target stimuli were forbidden (see Mayr et al. (2003)). Trials lasted until a response was given, or for a maximum of 2.2 s. An 800 ms mask separated the subsequent trials. The instruction was to avoid reading a word, and to press one of dedicated button(s) assigned to a presented color. The task was preceded by a training session which included 36 neutral trials (i.e., colored “HHHHHHH” strings), aimed to help participants to strengthen their S-R associations. Also, hints at the bottom of the screen (colored squares) reminded which colors are associated with which buttons, in order to decrease the working memory load of the task. The procedure warned participants each time they tried to persistently use only one and the same button to respond for the 2- or 3-button stimulus. The outline of the multiple-response Stroop task design is shown in Fig. 3.

The stimuli sequence included 192 no-conflict trials, in which the meaning of the word and the color were the same, so also the same were the number and identity of eligible buttons for both the color and the word, as well as 240 conflict trials with mismatching words and colors, in which the numbers of eligible responses for the color (X-) and incorrect responses for the word (-Y) differed. There were two independent variables: the number (1-, 2-, or 3-) of eligible buttons for colors, as well as the conflict level for a given number or target buttons: no conflict (the 1-1, 2-2, and 3-3 conditions), low conflict (the 1-2, 2-1, and 3-1 conditions), or high conflict (the 1-3, 2-3, and 3-2 conditions).

4.4. EEG recordings and data quantification and analysis

The continuous scalp electroencephalogram (EEG) was recorded from 32 silver/silver-chloride (Ag/AgCl) active electrodes (with pre-amplifiers) using the BioSemi Active-Two system: Fp1/Fp2, AF3/AF4, F3/F4, F7/F8, FC1/FC2, FC5/FC6, T7/T8, C3/C4, CP1/CP2, CP5/CP6, P3/P4, P7/P8, PO3/PO4, O1/O2, Fz, Cz, Pz, Oz. The electrodes were secured in an elastic cap (Electro Cap), according to the extended 10–20 international electrode placement system. The vertex electrode was used as a reference. The horizontal and vertical electro-oculograms (EOGs) were monitored using four additional electrodes placed above and below the right eye and in the external canthi of both eyes. The electrical signals were digitized within a sampling rate of 256 Hz. All channels were re-referenced off-line to the average of the two mastoid electrodes. The recordings were filtered off-line with a high-pass filter of 0.05 Hz (slope 24 dB/oct) and a low-pass filter of 25 Hz (slope 12 dB/oct). Artifacts were removed with the Independent Component Analysis algorithm (ICA) using the Brain Vision Analyzer 2 (Brainproducts, Munich, Germany).

Stimulus-locked segments (–100 ms to 1000 ms around the stimulus onset) were subsequently checked and averaged. Contaminated trials exceeding maximum/minimum amplitudes of $\pm 65 \mu V$ were rejected. ERPs were aligned to the 100 ms pre-stimulus baseline.

Within the signals recorded, we tested the PN, MFN, and SP components. After inspection of the grand-average waveforms and

scalp topography distributions, and following the extant literature on ERPs in the Stroop (see Larson et al. (2014), Pires et al. (2014)), especially West et al. (2012), PN was associated with a mean voltage between 400 and 480 ms after stimulus onset. MFN was quantified as a mean voltage between 480 and 540 ms. SP was indexed by a mean voltage between 650 and 850 ms. We used slightly later intervals than those proposed by West et al. for two reasons. First, our multi-response Stroop task was more complex than the counting Stroop task used by West et al., as suggested by longer RTs in our task (about 100 ms difference). Second, as in our data the peak of the N450 component was at about 480 ms, we wanted our PN component to represent the pre-peak negativity, whereas the MFN component – to reflect the post-peak negativity. Finally, following literature, we constrained our investigation to 8 centro-parietal electrodes measuring PN (left cluster: C3, CP1, P3; midline cluster: Cz, Pz; right cluster: C4, CP2, P4), 8 fronto-central electrodes tapping MFN (left cluster: F3, FC1, C3; midline cluster: Fz, Cz; right cluster: F4, FC2, C4), and 5 parietal electrodes capturing SP (left cluster: P3, PO3; midline electrode: Pz; right cluster: P4, PO4).

Analyzed EEG data thus represented brain activity (mean amplitudes in microvolts) that were averaged separately for each consecutive cluster of electrodes, for each component (PN, MFN, and SP), and for each of the nine task conditions. The effects of investigated experimental factors on the amplitude in selected time windows and electrode clusters were analyzed by means of 3 (eligible responses: 1, 2, or 3) by 3 (the conflict level: no, low, or high conflict) repeated measures ANOVA. For each analysis, we tested the three contrasts pertaining to the conflict level: the no-versus low-conflict condition, the no- versus high-conflict condition, and the low- versus high-conflict condition. We also searched for any significant interactions of the conflict level with the cluster factor (left, midline, right). Finally, for each investigated component we looked for the Gratton effect by testing the interactions between the conflict in the preceding trial (at two levels: no conflict vs. conflict, the latter covering all of the six low- and high-conflict conditions) and in the current trial (also at two levels: no conflict vs. conflict). The sizes of significant effects were reported using partial eta squared (η^2) in the cases of main effects and interactions, and using Cohen's *d* in the cases of contrasts.

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Author contributions

A.Ch. and M.S. conceived and designed the study. B.K. and M.O. prepared the experiment. P.K. conducted the experiment. A.Ch., M. S., P.K., B.K. and M.O. analyzed data and wrote the paper.

Conflict of interest

All authors declare no conflict of interest pertaining to this study.

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References

- Alexander, W.H., Brown, J.W., 2011. Medial prefrontal cortex as an action-outcome predictor. *Nat. Neurosci.* 14, 1338–1344.
- Banich, M.T., Milham, M.P., Atchley, R., Cohen, N.J., Webb, A., Magin, R., 2000. fMRI studies of Stroop tasks reveal unique roles of anterior and posterior brain systems in attentional selection. *J. Cognit. Neurosci.* 12, 988–1000.
- Bartholow, B.D., Pearson, M.A., Dickter, C.L., Sher, K.J., Fabiani, M., Gratton, G., 2005. Strategic control and medial frontal negativity: beyond errors and response conflict. *Psychophysiology* 42, 33–42.
- Berlyne, D.E., 1960. *Conflict, Arousal, and Curiosity*. McGraw-Hill, New York.
- Blais, C., Besner, D., 2006. Reverse Stroop effects with untranslated responses. *J. Exp. Psychol. Hum* 32, 1345–1353.
- Botvinick, M., Cohen, J.D., Carter, C.S., 2004. Conflict monitoring and anterior cingulate cortex: an update. *Trends Cogn. Sci.* 8, 539–546.
- Brown, J.W., Braver, T.S., 2007. Risk prediction and aversion by anterior cingulate cortex. *Cogn. Affect. Behav. Neurosci.* 7, 266–277.
- Chen, A., Bailey, K., Tiernan, B.N., West, R., 2011. Neural correlates of stimulus and response interference in a 2–1 mapping Stroop task. *Int. J. Psychophysiol.* 80, 129–138.
- Chuderski, A., Necka, E., 2010. Intelligence and cognitive control. In: A. Gruszka, G. Matthews, B. Szymura, (Eds.), *Handbook on Individual Differences in Cognition: Attention, memory, and executive control* (pp. 263–281). New York: Springer Verlag.
- Clayson, P.E., Larson, M.J., 2012. Cognitive performance and electrophysiological indices of cognitive control: a validation study of conflict adaptation. *Psychophysiology* 49, 627–637.
- Cohen, J.D., Botvinick, M., Carter, C.S., 2000. Anterior cingulate and prefrontal cortex: who's in control? *Nat. Neurosci.* 3, 421–423.
- Davelaar, E.J., 2008. A computational study of conflict monitoring at two levels of processing: reaction time distributional analyses and hemodynamic responses. *Brain Res.* 1202, 109–119.
- Eriksen, B.A., Eriksen, C.W., 1974. Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* 16, 143–149.
- Festinger, L., 1957. *A Theory of Cognitive Dissonance*. Stanford University Press, Stanford, CA.
- Festinger, L., Carlsmith, J.M., 1959. Cognitive consequences of forced compliance. *J. Abnorm. Soc. Psychol.* 58, 203–210.
- Gratton, G., Coles, M.G.H., Donchin, E., 1992. Optimizing the use of information: strategic control of activation of responses. *J. Exp. Psychol. Gen.* 121, 480–506.
- Grinband, J., Savitskaya, J., Wager, T.D., Teichert, T., Ferrera, V.P., Hirsch, J., 2011. The dorsal medial frontal cortex is sensitive to time on task, not response conflict or error likelihood. *NeuroImage* 57, 303–311.
- Hanslmayr, S., Pastötter, B., Bäuml, K.-H., Gruber, S., Wimber, M., Klimesch, W., 2008. The electrophysiological dynamics of interference during the Stroop task. *J. Cognit. Neurosci.* 20, 215–225.
- Hick, W.E., 1952. On the rate of gain of information. *Q. J. Exp. Psychol.* 4, 11–26.
- Holroyd, C.B., Coles, M.G.H., 2002. The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychol. Rev.* 109, 679–709.
- Jiang, J., Heller, K., Egner, T., 2014. Bayesian modeling of flexible cognitive control. *Neurosci. Biobehav. R.* 46, 30–43.
- Kane, M.J., Engle, R.W., 2003. Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *J. Exp. Psychol. Gen.* 132, 47–70.
- Kopp, B., Rist, F., Mattler, U., 1996. N200 in the flanker task as a neurobehavioral tool for investigating executive control. *Psychophysiology* 33, 282–294.
- Kornblum, S., Hasbroucq, T., Osman, A., 1990. Dimensional overlap: cognitive basis for stimulus-response compatibility – a model and taxonomy. *Psychol. Rev.* 97, 253–270.
- Larson, M.J., Clayson, P.E., Clawson, A., 2014. Making sense of all the conflict: a theoretical review and critique of conflict-related ERPs. *Int. J. Psychophysiol.* 93, 283–297.
- Larson, M.J., Kaufman, D.A., Perlstein, W.M., 2009. Neural time course of conflict adaptation effects on the Stroop task. *Neuropsychologia* 47, 663–670.
- Liotti, M., Woldorff, M.G., Perez, R., Mayberg, H.S., 2000. An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia* 38, 701–711.
- Logan, G.D., Zbrodoff, N.J., 1979. When it helps to be misled: facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Mem. Cogn.* 7, 166–174.
- MacLeod, C.M., 1991. Half a century of a research on the Stroop Effects: an integrative review. *Psychol. Bull.* 109, 163–203.
- Mayr, U., Awh, E., Laurey, P., 2003. Does conflict adaptation require executive control? *Nat. Neurosci.* 6, 450–452.
- Melara, R.D., Algom, D., 2003. Driven by information: a tectonic theory of Stroop effects. *Psychol. Rev.* 110, 422–471.
- Navon, D., 1977. Forest before trees: The precedence of global features in visual perception. *Cognit. Psychol.* 9, 353–383.
- Niendam, T.A., Laird, A.R., Ray, K.L., Dean, Y.M., Glahn, D.C., Carter, C.S., 2012. Meta-analytic evidence for a superordinate cognitive control network subserving

- diverse executive functions. *Cogn. Affect. Behav. Neurosci.* 12, 241–268.
- Pires, L., Leitao, J., Guerrini, C., Simoes, M.R., 2014. Event-related brain potentials in the study of inhibition: cognitive control, source localization, and age-related modulations. *Neuropsychol. Rev.* 24, 461–490.
- Proctor, R.W., 1978. Sources of color–word interference in the Stroop color-naming task. *Percept. Psychophys.* 23, 413–419.
- Schmidt, J.R., 2013. The Parallel Episodic Processing (PEP) model: dissociating contingency and conflict adaptation in the item-specific proportion congruent paradigm. *Acta Psychol.* 142, 119–126.
- Seymour, E.H., 1973. Stroop interference in naming and verifying spatial locations. *Percept. Psychophys.* 14, 95–100.
- Shor, R.E., 1971. Symbol processing speed differences and symbol interference effects in a variety of concept domains. *J. Gen. Psychol.* 85, 187–205.
- Stroop, J.R., 1935. Studies of interference in serial verbal reactions. *J. Exp. Psychol.* 18, 643–662.
- Szűcs, D., Soltész, F., White, S., 2009. Motor conflict in Stroop tasks: direct evidence from single-trial electro-myography and electro-encephalography. *Neuroimage* 47, 1960–1973.
- Tillman, C.M., Wiens, S., 2011. Behavioral and ERP indices of response conflict in Stroop and flanker tasks: response conflict in Stroop and flanker tasks. *Psychophysiology* 48, 1405–1411.
- Tzelgov, J., Henik, A., Berger, J., 1992. Controlling Stroop effects by manipulating expectations for color words. *Mem. Cogn.* 20, 727–735.
- Weissman, D.H., Giesbrecht, B., Song, A.W., Mangun, G.R., Woldorff, M.G., 2003. Conflict monitoring in the human anterior cingulate cortex during selective attention to global and local object features. *Neuroimage* 19, 1361–1368.
- Weissman, D.H., Gopalakrishnan, A., Hazlett, C.J., Woldorff, M.G., 2005. Dorsal anterior cingulate cortex resolves conflict from distracting stimuli by boosting attention toward relevant events. *Cereb. Cortex* 15, 229–237.
- West, R., 2003. Neural correlates of cognitive control and conflict detection in the Stroop and digit-location tasks. *Neuropsychologia* 41, 1122–1135.
- West, R., Alain, C., 1999. Event-related neural activity associated with the Stroop task. *Cogn. Brain Res.* 8, 157–174.
- West, R., Alain, C., 2000. Effects of task context and fluctuations of attention on neural activity supporting performance of the Stroop task. *Brain Res.* 873, 102–111.
- West, R., Bailey, K., Tiernan, B.N., Boonsuk, W., Gilbert, S., 2012. The temporal dynamics of medial and lateral frontal neural activity related to proactive cognitive control. *Neuropsychologia* 50, 3450–3460.
- West, R., Jakubek, K., Wymbs, N., Perry, M., Moore, K., 2005. Neural correlates of conflict processing. *Exp. Brain Res.* 167, 38–48.
- World Medical Organization, 1996. Declaration of Helsinki. *Brit. Med. J.* 313, 1448–1449.
- Van Veen, V., Carter, C.S., 2002. The timing of action-monitoring processes in the anterior cingulate cortex. *J. Cognit. Neurosci.* 14, 593–602.
- Van Veen, V., Cohen, J.D., Botvinick, M.M., Stenger, V.A., Carter, S., 2001. Anterior cingulate cortex, conflict monitoring and levels of processing. *Neuroimage* 14, 1302–1308.
- Yeung, N., Cohen, J.D., Botvinick, M.M., 2011. Errors of interpretation and modeling: a reply to Grinband et al. *NeuroImage* 57, 316–319.
- Yeung, N., Nieuwenhuis, S., 2009. Dissociating response conflict and error likelihood in anterior cingulate cortex. *J. Neurosci.* 29, 14506–14510.
- Yu, A.J., Dayan, P., Cohen, J.D., 2009. Dynamics of attentional selection under conflict: toward a rational Bayesian account. *J. Exp. Psychol. Hum.* 35, 700–717.