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Sequential conflict resolution under multiple concurrent conflicts:

An ERP study

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The experiment scripts, data, scripts analyses and results presented in this work can be found at <https://osf.io/gv46k>. Declarations of interest: none.

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Abstract

The purpose of the present study was to determine whether responding to multiple concurrent conflicts results in a simultaneous or sequential conflict resolution. To this end, we measured event-related potentials (ERPs) in a paradigm combining a Stroop and a flanker task. In this paradigm, participants were asked to respond to the color of the central letter while ignoring the meaning of the word (Stroop task) and the color of the flanking letters (flanker task). Trials were either incongruent (i.e., inducing a conflict between two response alternatives) or congruent (i.e., inducing no response conflict) in both tasks, or incongruent in one task and congruent in the other task. The behavioral results showed a smaller Stroop congruency effect (i.e., a smaller difference between Stroop incongruent and congruent trials) for flanker incongruent than for flanker congruent trials, replicating previous findings. The ERP results showed that an early ERP component (i.e., P2) was associated with the resolution of the flanker conflict, whereas a later component (i.e., N450) was associated with the resolution of the Stroop conflict. Together, these findings emphasize a sequential organization of conflict resolution processes in the brain which is adaptive when facing multiple concurrent conflicts.

Keywords: N2, N450, P2, Stroop, flanker

1. Introduction

Our society increasingly requires us to be multitaskers. For example, you can drive quickly but safely while following your navigation system. Moreover, you can slow down when approaching a red traffic light. However, if you see a police officer at the junction, you are able to ignore the traffic lights as well as the direction signaled by the navigation system in order to follow the officer's instructions. Thus, in everyday life, we encounter frequent situations in which we face multiple conflicts at the same time, such as encountering a police officer at a traffic lights junction while following the direction given by the navigation system. Resolving these conflict situations require us not only to detect the conflicts but also to make rapid decisions regarding how to react according to our current goals and then to select the appropriate response. To this end, we implement a multitude of control processes which are hierarchically organized in the prefrontal cortex (Badre, 2008; Koechlin & Summerfield, 2007). Cognitive control is among the core cognitive processes because it allows us to adapt to environmental changes in a fast and flexible way. The processes behind such adaptability include focusing attention on the relevant information as well as inhibiting competing alternatives or habitual responses. The purpose of the present study was to use event-related potentials (ERPs) to determine the precise neural time course of resolving multiple conflicts when these are presented concurrently.

Typically, conflict resolution is investigated using tasks such as the Stroop task (e.g., MacLeod, 1991; Stroop, 1935) or the flanker task (e.g., Eriksen & Eriksen, 1974). In the Stroop task, color words are printed in color, and participants are asked to indicate the ink color while ignoring the meaning of the word in order. In the flanker task, a row of characters is presented and participants are asked to respond to the central character while ignoring the flanking

characters. For example, participants may be asked to classify the color of the central letter while ignoring the color of the flanking letters. In both tasks, trials can be incongruent and thus induce a conflict between response features (e.g., the word “blue” printed in red for the Stroop task, or a red central letter flanked by blue letters for the flanker task). They can also be congruent and thus induce no conflict between responses (e.g., the word “red” printed in red for the Stroop task, or a red central letter flanked by red letters for the flanker task). The results showed slower and more error-prone performance on incongruent trials than on congruent trials. This difference in performance is called “congruency effect”.

To investigate how multiple concurrent conflicts are resolved, we developed a paradigm in which we combined a Stroop task with a flanker task (Rey-Mermet & Gade, 2016). That is, color words were printed in color and the color of the central letter was congruent or incongruent to the meaning of the word (Stroop task) and also congruent or incongruent to the color of the flanking letters (flanker task, see Figure 1 for an example). Participants were asked to indicate the color of the central letter while ignoring the meaning of the word and the color of the flanking letters. The results showed that the Stroop congruency effect was smaller – but still significant – when flanker trials were incongruent compared to when they were congruent. This indicates a sub-additive interaction between the two conflicts.

This interaction can be explained within the conflict monitoring framework (see, e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001) by assuming that the detection and/or resolution of one conflict has an impact on the resolution of the other conflict. That is, the conflict monitoring system evaluates the current levels of conflict for the first task to be processed. If this task is incongruent and thus associated with a high degree of conflict, this leads to a shift of control signal, triggering an adjustment in the strength of control for the second task

to be processed. In contrast, if the first task is congruent and thus associated with less conflict, there is an opposite effect on control, leading to less or no adjustment of control. Thus, according to this explanation, the flanker and the Stroop conflict would be processed *sequentially*, that is, in different and temporally separated processing stages. Separating the resolution of the two conflict types may have the benefit that each conflict can be resolved at the level at which it occurs. The flanker conflict can be prevented already by means of early spatial filtering (Botvinick et al., 2001), whereas the Stroop conflict is presumably resolved on the level of semantic categories (e.g., Brown & Besner, 2001; van Veen & Carter, 2005; Zhang & Kornblum, 1998). Theoretical accounts of cognitive control and attention frequently assumed that the level of conflict resolution can be adapted to specific task demands (Hübner, Steinhauser, & Lehle, 2010; Johnston & Heinz, 1978a; Lavie, Hirst, de Fockert, & Viding, 2004). Hence, a sequential organization of conflict resolution could represent an adaptive solution to situations with multiple concurrent conflicts.

There is, however, a more straightforward and parsimonious explanation to account for the interaction between the Stroop and flanker conflicts. Additive factor logic – an established framework for interpreting RT effects (Sternberg, 1969, 1998) – assumes that interactions in RTs can occur whenever two variables influence the same processing stage. Hence, the sub-additive interaction between flanker and Stroop conflict in RTs could reflect that the two conflicts are resolved in a single processing stage. For instance, both the flankers and the word meaning could activate their respective responses causing one response conflict that is resolved during response selection. In this case, the incongruent flankers and the incongruent word meaning would not be processed as distinct conflicts, but they would be resolved *simultaneously* at a single stage. However, whereas RT results could reflect an interaction of flanker and Stroop conflicts during

response selection, they do not necessarily imply that both conflicts are resolved at this stage.

To investigate whether the resolution of multiple concurrent conflicts occurs sequentially or simultaneously, we conducted the present study in which we used ERPs to track the neural time course of conflict resolution in the present paradigm. Previous research has revealed the involvement of at least three ERP components when responding to Stroop and flanker conflicts in isolation (see Larson, Clayson, & Clawson, 2014, for an overview). First, resolving the Stroop conflict has been related to an *N450*, a fronto-central negative-going deflection that peaks approximately 450 ms after stimulus onset (e.g., Larson, Kaufman, & Perlstein, 2009; Liotti, Woldorff, Perez III, & Mayberg, 2000; Markela-Lerenc et al., 2004; West, 2003; West, Bowry, & McConville, 2004; West, Jakubek, Wymbs, Perry, & Moore, 2005). That is, *N450* amplitudes are larger (i.e., more negative) for Stroop incongruent trials than for Stroop congruent trials. Second, resolving the flanker conflict has been related to an *N2*, a frontal negative-going deflection that emerges approximately between 250 ms and 350 ms after stimulus onset (e.g., Clayson & Larson, 2011; Gehring, Gratton, Coles, & Donchin, 1992; Kopp, Rist, & Mattler, 1996). Similar to the *N450*, *N2* amplitudes are larger for flanker incongruent trials than for flanker congruent trials. Both *N450* and *N2* have been associated to competing stimulus and/or response options (Larson et al., 2014; Van Veen & Carter, 2002). Recent research, however, has challenged the involvement of the *N2* in flanker conflict and instead put forward the role of the *P2* (Kałamała, Szewczyk, Senderecka, & Wodniecka, 2018). The *P2* is a frontal positive-going deflection that emerges approximately between 150 ms and 250 ms after stimulus onset and is typically associated to selective attentional processes engaged in stimulus evaluation (e.g., Gajewski, Stoerig, & Falkenstein, 2008; Luck et al., 1994; Potts, 2004).

We hypothesized that if the Stroop and flanker conflicts are resolved simultaneously, then

the resolution of both conflicts should be reflected in a single ERP component like, for example, the N2 or N450. In contrast, if the resolution of both conflicts occurs sequentially, we would expect that the resolution of one conflict is associated with an early ERP component, whereas the resolution of the second conflict is associated with a later ERP component. As the flanker task has been associated to early ERP components, such as the P2 or N2 (Kałamała et al., 2018; Larson et al., 2014), whereas the Stroop task has been associated to a later component (i.e., N450; see, e.g., Larson et al., 2014), we predicted that the flanker conflict would be the first to be resolved followed by the Stroop conflict.

2. Material and methods

The experiment scripts, data, scripts analyses and results presented in this work can be found at <https://osf.io/gv46k>.

2.1 Participants

Twenty-nine participants took part in the experiment. All participants had normal or corrected to normal vision and received payment (16 €) or course credit for participating in the experiment. We excluded four participants because they did not report German as native language, and one participant because of a technical problem. The final sample consisted of 24 participants (19 women, 23 right-handed, $\text{mean}_{\text{age}} = 24.3$ years, $\text{SD}_{\text{age}} = 3.4$). The study was conducted in accordance with the Declaration of Helsinki and informed consent was acquired from all participants.

2.2 Material

The stimuli consisted of the four German color words red, brown, violet, and white (i.e., “rot”, “braun”, “violett”, and “weiss”, respectively), displayed in red, brown, violet, or white color (see Figure 1 for examples). These colors were used in order to have words with an odd

number of letters and thus appropriate to create a flanker conflict. Thus, the middle letter of the German words (i.e., o for “rot”, a for “braun”, l for “violett”, and i for “weiss”) were displayed either in the same color as the meaning of the word (Stroop congruent) or in a different color (Stroop incongruent). Moreover, the flanking letters of the color words (e.g., “r” and “t” for “rot”) were presented either in the same color as the color of the middle letter (flanker congruent) or in a different color (flanker incongruent). In order to have the same number of flanker letters for each German color word, we added the symbol “#” twice on the left and right of the color word “red”, and once on the left and right of the color word “braun” and “weiss”. All stimuli were presented centrally on a black background in 21-point Courier New font in a gray or blue rectangle comprising a height of 1.15° visual angle and a width of 3.81° visual angle at a viewing distance of 60 cm (screen size: 41 x 30 cm, and screen resolution: 1280 x 1024 px).

2.3 Procedure

A trial sequence is illustrated in Figure 1. A trial started with the presentation of a yellow fixation cross for 500 ms, followed by the presentation of the stimulus. To prevent early offset-potentials, the stimulus disappeared 500 ms after a response was given. To respond, participants used four response keys (i.e., *f*, *g*, *j*, *k*), which were mapped to the colors red, brown, violet and white, respectively. In case of an error, the German word “Fehler” (*engl.* error) was displayed in yellow for 500 ms. Finally, an empty rectangle was presented during an intertrial interval of 500 ms.

Each experimental block included 74 trials (with two-warm-up trials at the beginning of the block). In each experimental block, there were four trial types, occurring with an equal probability of 25%: Stroop incongruent and flanker incongruent, Stroop incongruent and flanker congruent, Stroop congruent and flanker incongruent, Stroop congruent and flanker congruent

(see Figure 1). The stimulus for each trial was determined randomly. Moreover, 25% of the trials were catch trials in which the gray rectangle turned into blue. In these trials, participants were asked to indicate the meaning of the word while ignoring the color(s).¹ The catch trials were randomly interspersed in each block.

Participants performed 12 experimental blocks. An overall feedback, which consisted of mean reaction time (RT) and error rate, was displayed at the end of each block. Participants could take brief rests after each block. After having signed the informed consent sheet, participants first performed a practice block to learn the four-choice stimulus-response mapping. This block included 72 trials in which the stimuli consisted of a row of seven “x” colored in either red, brown, violet or white. Participants were instructed to indicate the color of the x’s. Then, participants performed two practice blocks with the same stimuli as for the experimental blocks. Participants were instructed to indicate the color of the central letter while ignoring the meaning of the word and the flanking letters.

Participants were tested individually in a sound-dim booth during one session of approximately two hours. The experiment was programmed using the E-prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) and run on IBM compatible computer.

2.4 EEG Data acquisition

Throughout the experiment, the electroencephalogram (EEG) was recorded with a BioSemi Active-Two system (BioSemi, Amsterdam, The Netherlands) using 64 electrodes from channels Fp1, AF7, AF3, F1, F3, F5, F7, FT7, FC5, FC3, FC1, C1, C3, C5, T7, TP7, CP5, CP3, CP1, P1, P3, P5, P7, P9, PO7, PO3, O1, Iz, Oz, POz, Pz, CPz, Fpz, Fp2, AF8, AF4, AFz, Fz, F2, F4, F6, F8, FT8, FC6, FC4, FC2, FCz, Cz, C2, C4, C6, T8, TP8, CP6, CP4, CP2, P2, P4, P6, P8, P10, PO8, PO4, O2, as well as the left and right mastoid. The CMS (Common Mode Sense) and

DRL (Driven Right Leg) electrodes were used as reference and ground electrodes. Vertical and horizontal electrooculogram (EOG) was recorded from electrodes above and below the right eye and on the outer canthi of both eyes. EEG and EOG were continuously recorded at a sampling rate of 512 Hz. All electrodes were off-line re-referenced to averaged mastoids.

2.5 Data preparation

For all behavioral and EEG dependent measures, the practice blocks and the warm-up trials were not analyzed. We also excluded catch trials and, to prevent effects of task switching, the first trial following a catch trial.

2.5.1 Behavioral data

For behavioral data, the dependent variables were reaction times (RTs) and error rates. We applied an arcsine square root transformation to the error rates for statistical analysis. For RTs, we additionally removed errors and one trial following an error from the raw data set. We also excluded RTs faster than 2.5 standard deviations (SD) from the mean and slower than 2.5 SD from the mean for each trial type and participant.

2.5.2 EEG data

EEG data were analyzed using custom-made MATLAB v8.5 (The Mathworks, Natic, MA, USA) scripts together with EEGLAB v13.4 (Delorme & Makeig, 2004) functions. The continuous EEG signal was band-pass filtered excluding frequencies below 0.1 Hz and above 40 Hz. Epochs were extracted ranging from -200 ms before to 600 ms after stimulus onset with a baseline interval from -200 to 0 ms. Electrodes were interpolated using spherical spline interpolation if they met either the joint probability criterion (threshold 5) or the kurtosis criterion (threshold 5) in EEGLAB's channel rejection routine (pop_rejchan.m). Epochs were removed that contained activity exceeding $\pm 300 \mu\text{V}$ in any channel except AF1, Fp1, Fpz, Fp2,

AF8 (to prevent exclusion of blink artifacts, which were corrected in a later stage) and whose joint probability deviated more than 5 standard deviations from the epoch mean. To correct for eye blinks and muscular artefacts, an infomax-based ICA (Bell & Sejnowski, 1995) was computed and components with time courses and topographies typical of these artefacts were removed after visual inspection. Similar to RTs, we removed epochs including an error and following an error as well as epochs in which the RT was faster than 2.5 SD from the mean RT and slower than 2.5 SD from the mean RT for each trial type and participant. Then, we averaged epochs separately for each trial type and each participant.

Following previous research (e.g., Kałamała et al., 2018; Kopp, Mattler, Goertz, & Rist, 1996; Larson et al., 2014, 2009), we computed three different ERPs: P2, N2, and N450. *P2* was computed as the mean amplitude at electrodes Fz, F1, F2, AFz and FCz in the time window ranging from 150 to 250 ms after stimulus onset. *N2* was computed as the mean amplitudes at electrodes Fz, F1, F2, AFz and FCz in the time window ranging from 250 to 350 ms after stimulus onset. *N450* was computed as the mean amplitudes at electrodes FCz, FC1, FC2, Fz and Cz in the time window ranging from 350 to 500 ms after stimulus onset.²

2.6 Data analysis

For all behavioral and ERP data, we investigated whether or not a Stroop congruency effect (i.e., a difference between Stroop incongruent and congruent trials), a flanker congruency effect (i.e., a difference between flanker incongruent and congruent trials) and an interaction between both Stroop and flanker tasks occurred. To this end, we first used a standard null-hypothesis significance testing (NHST) approach by carrying out a two-way repeated-measures analysis of variance (ANOVA) with the factors Stroop congruency (incongruent, congruent), and flanker congruency (incongruent, congruent). This was implemented in R (R Core Team, 2017)

with the afex package (Singmann, Bolker, & Westfall, 2018). An alpha level of 0.05 was used for all these tests. Effect sizes are expressed as η_g^2 values (generalized eta square, cf. Olejnik & Algina, 2003). In case of a significant interaction, follow-up *t*-tests were performed and effect sizes are expressed Cohen's *d*.

In addition, to assess not only the strength of evidence for the alternative hypothesis (e.g., the presence of the Stroop congruency effect) but also the strength of evidence for the null hypothesis (e.g., the absence of such effect), we used a Bayesian approach by computing a Bayesian ANOVA with default prior scales. This was implemented in R with the BayesFactor package (Morey & Rouder, 2015). To compute the Bayes Factor (BF) in favor of the alternative hypothesis (i.e., BF_{10}) for the main effect model including either the Stroop and flanker congruency, we compared the main effect model against the null model. To compute the BF_{10} for the interaction model, we compared the interaction model (i.e., the model with both main effects and the interaction) with the main effects model (i.e., the model with both main effects but no interaction) by calculating the ratio $BF_{\text{Interaction Model}} / BF_{\text{Main Effects Model}}$ (Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2017). For each model comparison, the Bayes Factor in favor of the null hypothesis (BF_{01}) was computed as $1/BF_{10}$. Following Raftery's (1995) classification scheme, we considered a BF between 1-3 as weak evidence, between 3-20 as positive evidence, between 20-150 as strong evidence, and larger than 150 as very strong evidence.

3. Results

For behavioral and ERP data, the most relevant results are the flanker congruency effect, the Stroop congruency effect, and the modulation of the Stroop congruency effect depending on whether the trials are flanker congruent or incongruent (i.e., the interaction between both

congruency variables). The descriptive results for the behavioral dependent measures (i.e., RTs and error rates) are presented in Figure 2. For the ERP measures, stimulus-locked waveforms at the electrodes of interest and scalp topographies are displayed in Figure 3. The results from the NHST and Bayesian analyses are presented in Table 1.

3.1 Behavioral data

The ANOVA showed that the interaction between Stroop congruency and flanker congruency was significant for the RTs only (see Table 1, upper part). In line with the NHST analysis, the Bayesian analysis reveals strong evidence in favor of this interaction (see Table 1). Thus, the Stroop congruency effect was smaller, but still significant, when the trials were flanker incongruent (114 ms), $t(23) = 7.12, p < .001, d = 1.45$, compared to when they were flanker congruent (228 ms), $t(23) = 8.25, p < .001, d = 1.68$ (see Figure 2). This was not affected by a speed-accuracy trade-off as the NHST analysis showed no significant interaction for error rates and the Bayesian analysis indicates positive evidence against the interaction model (see Table 1). Together, the behavioral results replicate our previous findings (Rey-Mermet & Gade, 2016).³

3.2 ERP data

3.2.1 P2.

Figure 3a shows a P2, that is, a pronounced positive-going deflection in the time window between 150 and 250 ms at the electrodes around Fz. Irrespective of whether the trials were Stroop incongruent or congruent, this P2 was more positive for flanker incongruent trials than for flanker congruent trials (see also the top scalp topography in Figure 3a). This was confirmed by the ANOVA showing a significant main effect of flanker congruency but neither a significant main effect of Stroop congruency nor an interaction (see Table 1). In line with the NHST analysis, the Bayesian analysis revealed strong evidence for the flanker congruency effect (see

Table 1).

3.2.2. N2.

Figure 3a also shows a negative-going deflection that emerges approximately between 250 ms and 350 ms at the electrodes around Fz. Although this deflection corresponds to a N2, it did not seem to vary according to flanker or Stroop congruency. In line with these descriptive results, the ANOVA showed no significant main or interaction effects, and the Bayesian analysis revealed positive evidence against a flanker congruency effect and against an interaction between both tasks. Together, the results indicate no differential effect on N2.

3.2.3 N450.

Figure 3b shows a more negative waveform for Stroop incongruent trials than for Stroop congruent trials in the time window between 350 and 500 ms at the electrodes around FCz. This corresponds to a larger N450 for Stroop incongruent trials, irrespective of whether the trials were flanker incongruent or congruent (see also the scalp topography in Figure 3b). This was confirmed by the ANOVA showing a significant main effect of Stroop congruency but neither a main effect of flanker congruent nor an interaction (see Table 1). In line with the NHST analysis, the Bayesian analysis revealed very strong evidence in favor of the Stroop congruency effect (see Table 1). Please note that, in line with previous studies (e.g., West, 2004), this difference in N450 is manifested in a sustained negative shift of the ERP rather than a phasic negativity.

4. General Discussion

In the present study, we combined a Stroop task with a flanker task to investigate the neural time course of resolving multiple concurrent conflicts. There are two possibilities how the resolution of flanker and Stroop conflicts is scheduled. Both conflicts could be resolved either simultaneously or sequentially. The latter implies that the resolution of one conflict is followed

by the resolution of the other conflict. To discriminate between these possibilities, we measured three different ERP components (i.e., P2, N2, and N450). While the behavioral results replicated the sub-additive interaction between both Stroop and flanker conflicts (see Rey-Mermet & Gade, 2016), the ERP results showed that the P2 was associated with the resolution of the flanker conflict, and the N450 was associated with the resolution of the Stroop conflict. These findings support the view of a sequential conflict resolution when multiple conflicts are presented concurrently.

In line with previous research (Larson et al., 2014, e.g., 2009; Liotti et al., 2000; Markela-Lerenc et al., 2004; West, 2003; West et al., 2004, 2005), we found that the N450 was associated with the resolution of the Stroop conflict, suggesting that the relevant color is activated while the irrelevant word meaning is suppressed. However, the resolution of the flanker conflict was not associated with a modulation of the N2 but rather with an effect on the P2. The null result for the N2 was confirmed by the Bayesian analysis. Although these findings might be surprising at first glance (cf. Clayson & Larson, 2011; Gehring et al., 1992; Kopp, Rist, et al., 1996; Larson et al., 2014), they are in line with a recent study (Kałamała et al., 2018) in which P2 – not N2 – was related to resolving a flanker conflict when flanker incongruent and congruent trials were equiprobable. As P2 has been associated to selective attentional processes engaged in stimulus evaluation (e.g., Gajewski et al., 2008; Luck et al., 1994; Potts, 2004), finding a conflict-related P2 instead of an N2 in the present study suggests that encountering the flanker conflict triggers early spatial attention which allows participants to focus on the target feature (i.e., on the color of the central letter; see Egnér & Hirsch, 2005).

These findings favor the idea of a sequential organization of conflict resolution processes when multiple conflicts are presented concurrently. Initially, there is a resolution of the flanker

conflict, which presumably occurs by means of early selective attention, as reflected by the P2. Then, the Stroop conflict is resolved by activating the relevant color and suppressing the irrelevant word meaning, as reflected by the N450. Such a sequential organization of conflict resolution has previously been suggested to account for behavioral data (Steinhauser & Hübner, 2005, 2007), and has been implemented in computational models of the flanker task (Hübner et al., 2010). The precise scheduling of conflict resolution processes might reflect an active, strategic adaptation of the brain to the type and magnitude of conflicts presented in our paradigm (see also Rey-Mermet & Meier, 2012, 2014, 2017b, 2017a; Rey-Mermet, Gade, & Oberauer, 2018). Theories on attention and cognitive control have proposed that the level of attentional selection (and thus conflict resolution) varies with task demands. For instance, low perceptual load leads to selection on a late, semantic level, whereas high perceptual load involves early selection such as perceptual filtering (Hübner et al., 2010; Johnston & Heinz, 1978b; Lavie et al., 2004). In the present paradigm, both types of selection were observed, which might reflect the attempt to resolve the respective conflicts as early as possible and on the level at which they occur.

This adaptive conflict resolution perspective provides a further explanation of why flanker conflict is represented by a P2 rather than by an N2 in our paradigm. Flanker conflict is driven by an additional stimulus dimension (the word). The resulting increase in perceptual complexity could have induced a conflict resolution strategy that counteracts the flanker conflict already via early perceptual filtering elicited by stimulus conflict (P2) rather than by inhibitory control driven by response conflict (N2). This would explain the discrepancy between the current results and another study that investigated concurrent conflicts. Frühholz, Godde, Finke, and Herrmann (2011) combined a flanker task with a Simon task, and found that the flanker conflict

was reflected in an N2, whereas the Simon conflict affected the P3. A Simon conflict occurs if the task-irrelevant position of a stimulus (e.g., left) is incongruent to the response side (e.g., right). As this type of conflict does not increase perceptual stimulus complexity, this paradigm might have induced a conflict resolution for the flanker conflict on a later level. Together, this suggests that, while the sequential organization of conflict resolution processes might be a general principle when multiple conflicts can occur, the specific stages (and involved ERP components) cannot be generalized across tasks.

The question arises why we obtained a sub-additive interaction between flanker congruency and Stroop congruency in the RTs while no such interaction was obtained in any of the ERP components. Indeed, we initially hypothesized that this interaction could reflect that the detection and/or resolution of one conflict has an impact on the resolution of the other conflict. However, if this were the case, we would have expected that both conflict effects become manifest in the same ERP components. A tentative way to explain the RTs is that the interaction does not emerge during conflict resolution, but appears on the level of motor responses. For instance, the flankers and the word could activate their respective motor responses via direct associations already during early stimulus processing (i.e., during P2 for the flanker conflict and N450 for the Stroop conflict; see Hübner et al., 2010). This pre-activation of motor responses then affects the duration of response selection or response execution, and in consequence RT. The sub-additive interaction in RTs could reflect that, for instance, if the incongruent flanker already strongly activated the incorrect response, only little additional activity can be added by the incorrect word meaning. Such an interactive effect is possible only because both effects of incongruency converge on the same motor representations (Cohen, Dunbar, & McClelland, 1990). Please note that such an explanation does not involve a joint conflict resolution

mechanism, it rather illustrates how interactive effects in behavioral data can emerge even when conflict resolution operates sequentially. Nevertheless, the interactive pattern in the RTs shows that RT data can be sensitive to aspects of information processing that are less evident in the ERP data.

The present results suggest a hierarchy of conflict resolution processes. When facing multiple concurrent conflicts, the brain recruits additional conflict resolution processes which are organized according to a temporal hierarchy. Thus, irrelevant stimulus features are first filtered out, and later the conflict on the level of semantic categories is resolved. This view bears some resemblance with the recently proposed hierarchical organization of control signals in the prefrontal cortex (Koechlin, Ody, & Kouneiher, 2003; Koechlin & Summerfield, 2007; see also Badre, 2008; Badre & D'Esposito, 2007, 2009). Koechlin and colleagues proposed that control signals in the prefrontal cortex are organized along a caudal-rostral gradient. With an increasing complexity of control demands, additional rostral areas are recruited. The question arises whether this representational hierarchy is related to the temporal hierarchy described in the present study. This could be addressed in future studies that identify prefrontal regions associated with the conflict resolution in the present paradigm.

5. Conclusion

To summarize, the results of the present study showed that when both Stroop and flanker conflicts are presented concurrently, conflict resolution proceeds in sequential processing stages. Whereas the flanker conflict is resolved in an early stage reflected by a modulation of the P2, the Stroop conflict is resolved in a later stage represented by a later N450. This pattern points to a hierarchical, sequential organization of conflict resolution processes in the brain which is adaptive when facing multiple concurrent conflicts.

6. Acknowledgements

This work was supported by a grant from the Swiss National Science Foundation (Grant P300P1_164598) to A. Rey-Mermet. The authors thank Rebekka Eilers for her help in data collection and Robert Steinhauser for the MATLAB scripts.

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Footnotes

¹ In the present study, the Stroop conflict results from the competition between the color of the central letter and the meaning of the word. Previous research has revealed that this single-letter Stroop task can reduce the Stroop congruency effect (Besner, Stolz, & Boutilier, 1997). Therefore, to make the meaning of the word as salient as possible and thus to enhance conflict in incongruent trials, we included catch trials in Rey-Mermet and Gade (2016). For the same reasons, we also included catch trials in the present study.

² Computing P2 and N2 as the mean amplitudes at electrode Fz and N450 as the mean amplitudes at electrode FCz did not change the pattern of results.

³ In Rey-Mermet and Gade (2016), we checked for the impact of the previous congruency on the interaction between Stroop and flanker congruency, and we found that the interaction was not further modulated by the previous Stroop or flanker congruency. For the sake of comparison, we computed the same analysis with the present behavioral data. That is, we analyzed these effects after removing the impact of episodic memory of stimulus-response associations by excluding trials with partial feature repetitions (i.e., trials in which the target color, the flanker color, or the word meaning repeated) and trials with negative priming (i.e., trials in which either the flanker color or the word meaning of the previous trial became the target color of the current trial). This dismissed 63.6% of the trials and five participants because of missing data. We computed a four-way repeated-measures ANOVA with the factors Stroop congruency (incongruent, congruent), flanker congruency (incongruent, congruent), Stroop previous congruency (incongruent, congruent) and flanker previous congruency (incongruent, congruent). The ANOVA showed no three-way or higher-order interaction involving Stroop congruency and flanker congruency (see the results at <https://osf.io/gv46k>). The number of trials was too small to

perform a similar analysis on the ERPs.

SEQUENTIAL CONFLICT RESOLUTION

Table 1

Inferential statistical for the 2-way repeated-measures analysis of variance (ANOVA) with the factors Stroop congruency (incongruent, congruent) and flanker congruency (incongruent, congruent) and Bayes factors (BF) for behavioral data (i.e., reaction times and error rates) and ERPs (i.e., P2, N2, and N450).

Dependent Measure	Effect/Model	ANOVA			Bayesian analysis	
		<i>F</i>	<i>p</i>	η_g^2	BF ₁₀	BF ₀₁
Reaction times	Stroop congruency	82.45	<.001	.22	2.17e+11	4.62e-12
	Flanker congruency	5.25	.031	.01	0.51	1.96
	Interaction	21.07	<.001	.03	37.37	0.03
Arcus-sinus transformed error rates	Stroop congruency	61.51	<.001	.31	8.75e+07	1.14e-08
	Flanker congruency	6.52	.018	.07	3.34	0.30
	Interaction	0.08	.780	<.001	0.29	3.45
P2	Stroop congruency	0.17	.685	<.001	0.22	4.55
	Flanker congruency	11.09	.003	.01	22.79	0.04
	Interaction	0.004	.949	<.001	0.29	3.45
N2	Stroop congruency	2.09	.162	.002	0.75	1.33
	Flanker congruency	0.16	.691	<.001	0.22	4.55
	Interaction	0.44	.515	<.001	0.33	3.03
N450	Stroop congruency	14.28	<.001	.02	186.96	0.01
	Flanker congruency	0.07	.794	<.001	0.22	4.55
	Interaction	0.003	.954	<.001	0.29	3.45

Note. *dfs* = (1, 23) for the *F* statistic. Effect sizes are expressed as generalized η^2 values. BF₁₀ =

SEQUENTIAL CONFLICT RESOLUTION

Bayes Factor in favor of the alternative hypothesis (i.e., in favor of the effect). BF_{01} = Bayes Factor in favor of the null hypothesis (i.e., in favor of the absence of the effect).

Figure 1. Example of one trial sequence. Participants were asked to indicate the color of the letter in the middle while ignoring the meaning of the word and the flanking letters. The top panel shows example of stimuli for each trial type (Stroop incongruent – flanker incongruent, Stroop congruent – flanker congruent, Stroop congruent – flanker incongruent, and Stroop congruent – flanker congruent).

Figure 2. Modulation of the Stroop congruency effect by flanker congruency within a trial. Mean reaction times (RT, top part) and mean raw error rates (bottom part) for both Stroop and flanker congruency. Error bars represent within-subject confidence intervals (see Cousineau, 2005; Morey, 2008).

Figure 3. ERP results. (A) P2 and N2: Mean stimulus-locked ERP waveforms (left part) and mean amplitudes (middle part) at the electrodes Fz, F1, F2, AFz and FCz, as well as scalp topographies (right part) for the flanker congruency effect in the time window 150 – 250 ms (top part) and 250 – 350 ms (bottom part). (B) N450: Mean stimulus-locked ERP waveforms (left part) and mean amplitudes (middle part) at the electrodes FCz, FC1, FC2, Fz, and Cz, as well as a scalp topography for the Stroop congruency effect in the time window 350 – 500 ms. Gray areas highlight the a priori time windows for each ERP of interest.