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Adaptive cognitive control attenuates the late positive potential to emotional distractors

Tobias Flaisch [a,*], Marco Steinhauser [b], Harald T. Schupp [a]

[a] Department of Psychology, University of Konstanz, 78464, Konstanz, Germany
[b] Department of Psychology, Catholic University of Eichstätt-Ingolstadt, 85072, Eichstätt, Germany

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ABSTRACT

Emotional pictures are inherently prioritized during stimulus perception. While this preferential emotion processing promotes self-preservation and survival, it can be detrimental when it conflicts with current goals and intentions. Recent brain imaging research suggests that the brain resolves such conflicts by suppressing the processing of emotional distractors at the perceptual level. Beyond brain imaging, event-related scalp potential studies in humans have traced preferential emotion processing at distinct temporal stages. Comparing emotional to neutral pictures, an early stage is indexed by the early posterior negativity (EPN) component featuring a relative negativity over posterior sites, while a later stage is associated with the late positive potential (LPP), manifesting as relative positivity over centro-parietal sensors. However, little is known whether emotional response conflict is resolved at each of those processing stages, or whether conflict resolution operates selectively at early or late stages, respectively. The present study assessed EPN and LPP to emotional distractors in an emotional Stroop task as a function of response conflict in the previous trial. Conflict-related processing during the Stroop task was confirmed by a behavioral conflict adaptation effect and modulation of the congruency-sensitive N450 component. Preferential processing of emotional distractors was observed for the EPN as well as the LPP. While the EPN was completely unaffected by conflict in the previous trial, the LPP was selectively reduced subsequent to trials featuring high response conflict. This observation provides support for a conflict-based control of emotion processing and demonstrates that cognitive control acts selectively at specific stages of emotion perception.

1. Introduction

Cognitive control mechanisms facilitate the flexible organization of task performance according to current goals and intentions. A viable framework to examine these mechanisms is the conflict monitoring theory (Carter et al., 1998; Botvinick et al., 2001). It assumes that a conflict monitoring system in the dorsal anterior cingulate cortex (dACC) registers response conflict emerging when contradictory behavioral tendencies become activated simultaneously, and then strengthens cognitive control to prevent the occurrence of further conflict. Conflict conditions have been created in tasks inducing different incompatible responses. For instance, in the classic Stroop test, response incompatibility is attained by presenting color words in a color differing from their word meaning (Stroop, 1935). In according studies, an incongruency between color and meaning leads to diminished task performance, which, however, is attenuated if the previous trial was also incongruent (Kerns et al., 2004). Corresponding observations in this and other conflict tasks have been taken as an indication for conflict adaptation (Gratton et al., 1992), i.e., the brain's capacity to monitor and control the interfering impact of conflicting information.

The implementation of control in conflict adaptation depends on the specific nature of the distracting information (Soutschek and Schubert, 2013). At the neural level, non-emotional conflicts recruit selective attention in the dorsolateral prefrontal cortex (Gbadeyan et al., 2016; Kerns et al., 2004) which enhances activation of task-relevant information (Egner and Hirsch, 2005). In contrast, control of emotional conflicts presumably involves the rostral anterior cingulate cortex which inhibits processing of irrelevant emotional information in the amygdala (Egner et al., 2008; Etkin et al., 2006) and visual processing areas (Steinhauser et al., 2016). For instance, a recent fMRI study showed that preferential processing of emotional as compared to affectively neutral distractor pictures was attenuated in extrastriate visual cortex subsequent to

* Corresponding author. University of Konstanz, Department of Psychology, Fach 36, D-78457, Konstanz, Germany.
E-mail address: Tobias.Flaisch@uni-konstanz.de (T. Flaisch).

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incongruent trials (Steinhauser et al., 2016). While lower-level visual areas of the striate cortex also showed preferential emotion processing, this remained unaffected by conflict adaptation. This implies that emotional conflict resolution encompasses the down-regulation of preferential processing of task-irrelevant pictures in higher-order visual cortex (Banich et al., 2019). However, while these effects emerge at an anatomically early stage of the visual stream, it is still unclear whether they modulate the initial affective tagging and/or later elaborative processing of stimuli.

The current study investigated the neural time course of top-down control over preferential emotional processing in conflict adaptation by considering two ERP components sensitive to emotional stimulus significance: the early posterior negativity (EPN) and the late positive potential (LPP; Schupp et al., 2006). The EPN reflects early initial tagging of affective stimuli and is typically observed over temporo-parieto-occipital sensors at 150–350 ms after stimulus onset as a more negative-going deflection of the surface potential when viewing emotional as compared to neutral pictures (Flaisch et al., 2008a, 2008b; Schupp et al., 2007a, 2007b). Reflecting elaborative processing, the LPP emerges at 350–750 ms over fronto-centro-parietal positions as a relative positivity to emotional stimuli (Flaisch et al., 2008b; Schupp et al., 2007b). While numerous studies suggest that top-down effects of cognitive control interact with preferential emotion processing at the level of the LPP (Hajcak et al., 2010; Schindler and Kissler, 2016; Schupp et al., 2007b), according observations for the EPN are comparably sparse (Schupp et al., 2007a, 2014). Moreover, none of these studies has investigated how dynamic adjustments of top-down control are achieved. Here, we investigated whether top-down control as observed in modulations of these ERP components is guided by a similar conflict monitoring mechanism as demonstrated in Steinhauser et al. (2016).

To this end, participants were asked to categorize two emotional words, which were overlaid over emotional and neutral background images (Steinhauser et al., 2016). The task-irrelevant background images served as distractors, which, in the case of emotional images, were congruent or incongruent to the target word. This allowed assessing effects of conflict adaptation on emotion processing by analyzing involuntary preferential processing of distractor images as a function of the congruency of the previous trial. If conflict resolution mechanisms exert top-down influence on the processes underlying the EPN and LPP, respectively, this should be observed as a relatively diminished ERP difference between emotional and affectively neutral distractors subsequent to incongruent, as compared to congruent and neutral previous trials.

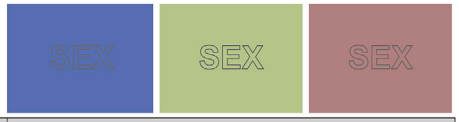
2. Methods

2.1. Participants

Twenty-six right-handed participants (11 male) between 19 and 32 years of age (M = 23.5) with normal or corrected-to-normal vision participated in the study. Participants were recruited at the University of Konstanz and received course credit or monetary compensation. Sample size was larger than previous studies on the EPN/LPP (e.g., Schupp et al., 2007b; Sussman et al., 2017; Weinberg et al., 2012) and on conflict adaptation with affective stimuli (e.g., Egner et al., 2008; Etkin et al., 2006). The study was approved by the ethics committee of the University of Konstanz. Before the experiment, all participants were informed about the procedure. After they had been thoroughly familiarized with a number of exemplary pictures representative of the experimental picture set, written informed consent was obtained from all participants.

2.2. Stimuli

The picture set comprised 36 colored pictures overall, containing 12 pleasant, 12 neutral and 12 unpleasant images. With the exception of 3 neutral pictures (displaying a roll of splicing tape, a hole puncher, pliers),



Distractor Category	household	erotic	mutilation
Distractor Emotionality	neutral	emotional	emotional
Stimulus Congruency	neutral	congruent	incongruent
Response Conflict	low	low	high

Fig. 1. Exemplary overview of Stroop stimuli using the target word SEX and the ensuing experimental classifications. Please note that the colored backgrounds serve as place holders for the picture categories. Due to copyright issues, IAPS pictures may no longer be propagated in scientific publications. The full list of used IAPS pictures is provided in Footnote 1.

all stimuli were taken from the International Affective Picture System library (Lang et al., 2008).[1] Pleasant stimuli depicted couples in erotic poses. Neutral stimuli displayed everyday household objects, and unpleasant stimuli showed images of mutilated people. At the beginning of the session, participants were asked to rate the pictures according to their pleasantness and arousal using the Self-Assessment Manikin rating scale (Bradley and Lang, 1994). In accordance with a-priori selection criteria, analysis-of-variance (ANOVA) with repeated measurement on the variable *Picture Category* (erotic vs. neutral vs. mutilation) confirmed that the picture categories differed in terms of valence (F (2, 50) = 345.6, $p < .001$, $\eta_p^2 = 0.47$). Posthoc testing (Tukey HSD) revealed, that erotic images (M = 6.7, SD = 0.87) were rated as more pleasant than household objects (M = 5.0, SD = 0.37; p < .001), which, in turn were perceived as more pleasant than the mutilation pictures (M = 1.8, SD = 0.54; p < .001). The three categories also differed with regard to their perceived arousal (F (2, 50) = 96.7, $p < .001$, $\eta_p^2 = 0.4$). While both, erotic (M = 5.3, SD = 1.40) and mutilation (M = 6.8, SD = 1.57) images were rated as more arousing than household objects (M = 2.1, SD = 1.41; p's < 0.001), arousal was higher for mutilation than for erotic images ($p < .001$).

The multidimensional Stroop stimuli for the main experiment were generated by combining each picture with the German words SEX (engl. sex) and TOD (engl. death), written with capital letters in gray Arial font (Fig. 1). Again using the SAM scale, a subset of participants (n = 18) also rated these target words which were complemented by the word HUT (engl. hat) to provide a neutral anchor for the self-report. Repeated-measure ANOVA showed, that target words differed with regard to perceived valence (F (2, 34) = 133.0, $p < .001$, $\eta_p^2 = 0.44$). Specifically, posthoc testing (Tukey HSD) showed that SEX (M = 7.3, SD = 1.14) was rated as more pleasant than HUT (M = 4.9, SD = 0.47; $p < .001$), which in turn was rated as more pleasant than TOD (M = 1.7, SD = 1.07; $p < .001$). With regard to arousal (F (2, 34) = 41.4, $p < .001$, $\eta_p^2 = 0.35$), SEX (M = 6.8, SD = 1.70) and TOD (M = 5.7, SD = 2.08) were more arousing than HUT (M = 1.8, SD = 1.40; $ps < .001$), but did not differ from each other ($p = .147$).

To prevent participants from focusing on the target words and thus fully blanking out the background pictures (Cesarei et al., 2009; Schupp et al., 2014), the words were printed centrally as contours thus letting the background picture show through (Fig. 1). The resulting 72 Stroop

[1] Full List of IAPS pictures. Pleasant: 4611, 4650, 4653, 4658, 4659, 4660, 4669, 4680, 4690, 4694, 4695, 4800; Unpleasant: 3000, 3010, 3030, 3051, 3053, 3060, 3069, 3071, 3100, 3110, 3120, 3130; Neutral: 7000, 7004, 7006, 7009, 7010, 7030, 7031, 7041, 7050.

stimuli consisted of three stimulus categories: In neutral stimuli, the background picture was not emotional and thus was neither congruent nor incongruent with respect to the overlaid word. In congruent stimuli, the background picture was emotional and corresponded semantically to the word. In incongruent stimuli, the background picture was emotional but differed semantically from the word (Fig. 1). Using Presentation software (Neurobehavioral Systems, Inc., Albany, CA), stimuli were presented on a 21-inch CRT-monitor (75 Hz refresh rate) located approximately 120 cm in front of the participant. At a resolution of 800 × 600 pixels, the background pictures subtended a vertical visual angle of 10.9° and a horizontal visual angle of 14.6°, while the overlaid words subtended vertically 2.4° and horizontally 6.7°.

At the beginning of the experimental run, participants passively viewed the background pictures devoid of the target words in a continuously presented stream to provide the assessment of the EPN and LPP components uncontaminated by word processing and task requirements. Specifically, each picture was presented for 694 ms, followed by a blank screen for 317 ms. The stream consisted of 360 pictures in pseudo-randomized order in which no picture category could occur more than three times in succession. Thus, each picture from the three categories was presented ten times.

After this, the Stroop experiment was started. Participants were required to discriminate between the words SEX and TOD while ignoring the task-irrelevant background pictures of the compound Stroop stimulus. Participants were instructed to respond as fast as possible by pressing mouse buttons with the index or the middle finger of the right hand, respectively. In half of the participants, SEX required responding with the index finger, and TOD required responding with the middle finger. In the other half, the mapping was reversed. To direct the participants' attention to the center of the screen, each trial was preceded by a cue, which displayed the corners of a gray box on a black background. The cue box was presented 200 ms before stimulus onset, visually framing the position of the word in the upcoming Stroop stimulus. Then, the Stroop stimulus was displayed for 706 ms after which a black screen was shown. If the participant responded within the presentation time of the Stroop stimulus, a black screen followed the stimulus with a variable inter-stimulus interval of 95–800 ms. If the response occurred after stimulus presentation, the next cue stimulus was shown 800 ms after the response. Due to a programming error, the response-stimulus interval (RSI) differed between conditions (range: 840–853 ms). We thus re-conducted all analyses with a subset of trials matched for RSI across experimental conditions. These control analyses fully confirmed all reported effects ruling out an impact of RSI with regard to the research questions. To familiarize the participants with the experimental task, 12 practice trials were presented before the start of the first block. Afterwards, participants worked through 1440 experimental trials, divided in six blocks consisting of 240 trials each. Each block started with an additional neutral dummy trial, which was not entered into data analysis. Each block was followed by a short break to allow participants to rest and to adjust their posture.

2.3. Recording and data analysis

Brain and ocular scalp potentials were measured with a 256-lead geodesic sensor net (GSN 200 v2.0; EGI: Electrical Geodesics, Inc., Eugene, OR), on-line bandpass filtered from 0.01 to 100 Hz, and sampled at 250 Hz using Netstation acquisition software and EGI amplifiers. Electrode impedance was kept below 30 kΩ, as recommended for this type of electroencephalogram (EEG) amplifier by EGI guidelines. Data were recorded continuously with the vertex sensor as reference electrode. Continuous EEG data were low-pass filtered at 35 Hz using a zero-phase forward and reverse digital filter before stimulus synchronized epochs were extracted. Data editing and artifact rejection were based on a two-step method for statistical control of artifacts (Junghoefer et al., 2000). In a first pass of the data (using the recording reference), sensors contaminated across the session were identified and rejected. Furthermore, sensors containing trial epochs with artifact activity were rejected to avoid contamination when converting the data to an average reference. The rejection of artifact-contaminated epochs was based on the thresholds for a number of statistical parameters (Junghoefer et al., 2000). In a second pass, based on the average referenced data, sensors containing artifact-contaminated activity were replaced using spherical interpolation based on all remaining sensors for the given trial. For each experimental cell, average waveforms were calculated for each sensor and participant. Error and post-error trials were eliminated from statistical analysis.

2.3.1. Passive viewing

Since preferential emotion processing as indexed by the EPN and LPP is subject to considerable interference by active task requirements and physical stimulus manipulations (Cesarei and Codispoti, 2006; Schupp et al., 2007a, 2007b, 2008, 2014), a precise assessment necessitates identifying both components undeterred by these factors. Specifically, since we were interested in the incidental processing of task-irrelevant background pictures, we strived to characterize the ensuing ERP signature independent from additional processes entailed by the Stroop task. We thus used the data acquired during the viewing of the initial passive picture stream to detail processing differences between emotional and neutral pictures in terms of latency and topography. Our reasoning was that the electrocortical signature of incidental emotional picture processing during the Stroop task would be subject to interference and would be superposed and obscured by effects of directed attention, perceptual and semantic word processing and response execution. Accordingly, modulation by emotion as observed during the passive picture viewing should represent underlying processes in a comparably unbiased fashion. Towards this end, we collapsed pleasant and unpleasant images and compared the associated ERPs to those evoked by neutral pictures. An early and a relatively later modulation became readily apparent during visual inspection of the ERPs and the difference waves ([emotional-neutral]; Fig. 2). The former was characterized by a relative negative going deflection over bilateral posterior sensor sites in the time frame of 150–350 ms post stimulus onset and had its maximum peak at around 220 ms (Fig. 2A). The latter was observed in the time frame of 300–750 ms as a relative positive deflection over centro-parietal sites. This modulation appeared maximal between 400 and 700 ms with an apparent magnitude shift at around 550 ms and its topography extended distinctly further over right-hemispheric sensors (Fig. 2B). Based on these observations, we derived sensor clusters and time intervals that were optimized to capture the specific empirical appearance of the EPN and LPP components (Fig. 2), while also maximizing comparability with previous research.

For the EPN we thus analyzed a posterior sensor cluster in the time interval of 200–300 ms (EGI sensors: 107, 113, 114, 115, 116, 120, 121, 122, 123, 124, 125, 133, 134, 135, 136, 137, 138, 145, 146, 147, 148, 149, 150, 156, 157, 158, 159, 160, 165, 166, 167, 168, 174, 175, 176, 187).

As the EPN is typically associated with a polarity-reversed positivity over widely distributed fronto-centro-parietal sites, it often shows some temporal and topographical overlap with subsequent LPP-related modulations (see e.g. Flaisch et al., 2008a; Schupp et al., 2007b). For this reason, clearly disambiguating EPN-related polarity-reversal and LPP-modulation is often difficult at according sensors. Thus, our interval selection for the LPP additionally sought to temporally separate EPN and LPP. Together with inter-study comparability, this consideration informed the decision to score the LPP at a somewhat later time point as observed based on visual inspection. Consequently, we analyzed the LPP from 400 to 700 ms in a slightly right-lateralized centro-parietal sensor cluster (EGI sensors: 80, 81, 89, 90, 100, 101, 110, 119, 127, 128, 129, 130, 131, 132, 139, 140, 141, 142, 143, 144, 150, 151, 152, 153, 154, 155, 160, 161, 162, 163, 164, 170, 171, 172, 173, 179, 180).

To corroborate the visually observed localizer-based emotion effects

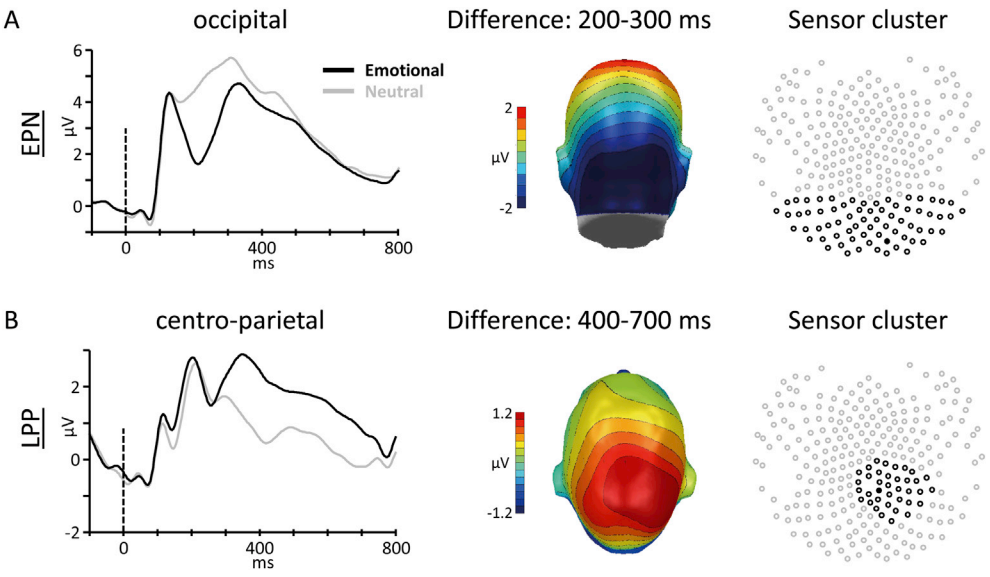


Fig. 2. Emotional ERP-modulation during passive picture viewing in the localizer task. Left panel: Event-related potentials at representative occipital (EGI# 168) and centro-parietal (EGI# 129) sensors reveal the time course of the EPN (A) and LPP (B).
Middle panel: Surface plots of the difference waves [emotional-neutral] in corresponding time windows illustrate the topography of the EPN (back view) and LPP (top view).
Right panel: For the main analysis, the EPN was captured in a posterior sensor cluster, and the LPP in a slightly right-lateralized centro-parietal sensor cluster. Brimmed black dots indicate the locations of the sensors displayed in Figs. 2 and 5.

statistically, we analyzed the data from the passive viewing part utilizing a paired-groups *t*-test comparing the ERPs to emotional and neutral pictures for the EPN and the LPP, respectively.

2.3.2. Emotional stroop task

2.3.2.1. N450

A widely studied indicator of Stroop-related conflict processing is the N450 component (Folstein and van Petten, 2008). Comparing incongruent to congruent stimuli, it is observed as a relative negativity at around 450 ms over central positions. To assess whether the brain detected the emotional incongruency of the Stroop stimuli, we examined the N450 comparing congruent and incongruent current trials in the Stroop task. Visual inspection indicated according ERP differences at pertinent sensor locations and time windows (Fig. 3). For statistical corroboration, we calculated a paired-groups *t*-test in a time window from 400 to 428 ms in a frontocentral sensor cluster (EGI sensors: 8, 9, 17, 44, 45, 53, 80, 81, 89, 90, 130, 131, 132, 144, 185, 186, 198, 257).

2.3.2.2. EPN & LPP

To analyze the data from the Stroop task, we then relied on the independently determined clusters and time intervals from the passive viewing experiment and followed the same pre-defined analysis path for both the EPN and LPP, respectively. We first tested whether it was feasible to collapse congruent and incongruent current trials by calculating a 3 × 2 repeated measures ANOVA including the variables *Previous Trial Category* (neutral, congruent, incongruent) and *Current Trial Congruency* (congruent, incongruent). If this failed to yield significant effects, we then collapsed congruent and incongruent current trials and tested our research hypothesis by conducting a 3 × 2 repeated-measures ANOVA which included the variables of *Previous Trial Category* (neutral, congruent, incongruent) and *Current Trial Emotionality* (emotional, neutral). Based on ample evidence suggesting that varying functional mechanisms may underlie early and late time-sections of the LPP (see e.g., Hajcak et al., 2010; Sussman et al., 2017; Uusberg et al., 2013; Weinberg et al., 2012) we wanted to additionally explore the possibility that adaptive cognitive control acts exclusively at either time section. For analyzing the LPP in the Stroop task, we thus included the variable *Time* in the according ANOVA. To this end, we split the 400–700 ms interval into two equally sized bins. At a sample rate of 250 Hz, this resulted in two time windows of identical length, i. e., 400–548 ms (early LPP) and 552–700 ms (late LPP), each incorporating 38 analyzed time points, respectively. Significant effects were followed up by means of posthoc comparisons utilizing Tukey's HSD. Where appropriate, the Huynh-Feldt procedure was applied to correct for violations of sphericity.

2.3.3. Behavioral analyses

A robust indicator for cognitive control induced by conflict monitoring is the behavioral conflict adaptation effect (Gratton et al., 1992), which refers to the finding that the effect of response conflict on the current trial is reduced if response conflict was high on the previous trial. We thus additionally analyzed response times (RT) and error rates. For computing mean RTs, we excluded error and post-error trials, as well as trials with RTs less than or greater than 2.5 standard deviations below or

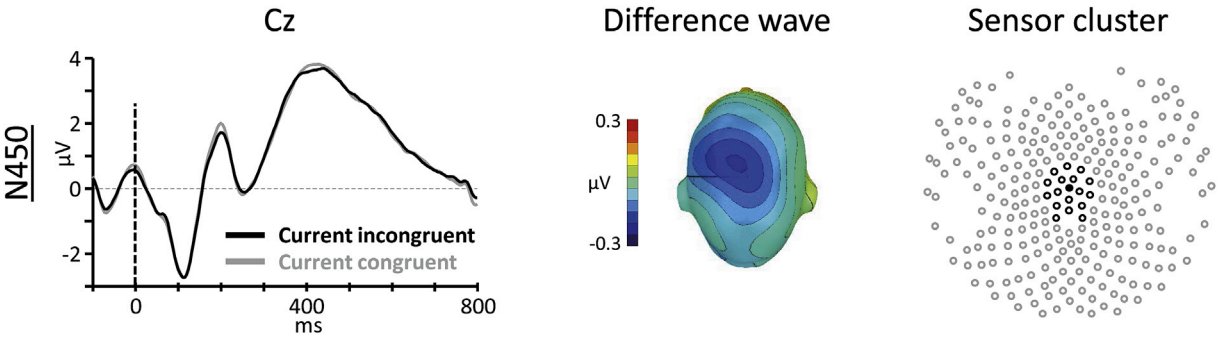


Fig. 3. ERP-modulation during the processing of current trials in the Stroop task as a function of stimulus congruency. ERPs (Cz; left panel) and surface plot (top view; middle panel) of the difference wave [incongruent – congruent] in the analyzed time window (400–428 ms) reveal time course and topography of the N450 congruency effect. The sensor montage (right panel) indicates sensors selected for cluster analysis.

above the mean, determined separately for each condition and participant. Across conditions and participants, 5.4% of trials were excluded on average. Before analyzing error rates, arcsine transformation was applied to the data (Sokal and Rohlf, 1981). Our analysis contrasted stimuli with high response conflict (i.e., incongruent) with stimuli with low response conflict (i.e., neutral, congruent) in the current or previous trial. Thus, we conducted 2 × 2 repeated-measures ANOVAs with the variables *Previous Response Conflict* (low, high) and *Current Response Conflict* (low, high). As with the ERP analyses, significant effects were followed up by means of posthoc comparisons utilizing Tukey's HSD.

3. Results

3.1. Behavioral data

We obtained conflict adaptation effects in the RTs. Specifically, RTs were increased for high-conflict as compared to low-conflict trials following low-conflict trials. In contrast, such an effect was absent following high-conflict trials (Fig. 4). Specifically, a main effect of *Previous Response Conflict* (F (1, 25) = 19.1, $p < .001$, $\eta_p^2 = 0.43$) was further qualified by a significant interaction of *Previous* by C*urrent Response Conflict* (F (1, 25) = 6.3, $p = .019$, $\eta_p^2 = 0.2$). Posthoc tests (Tukey HSD) confirmed that the difference in current response conflict was significant if previous response conflict was low ($p = .013$, $M_{lo} = 429$, $SD_{lo} = 37$, $M_{hi} = 434$, $SD_{hi} = 38$), while no such effect was obtained if previous response conflict was high ($p = .997$, $M_{lo} = 438$, $SD_{lo} = 39$, $M_{hi} = 437$, $SD_{hi} = 39$). The same analyses conducted for the error rates revealed no significant results, neither for the main effects (F's < 0.83, p's > 0.37), nor for the interaction (F (1, 25) = 2.69, $p = .113$, $\eta_p^2 = 0.1$).

Conflict adaptation effects can potentially reflect stimulus priming (Mayr et al., 2003), because stimulus repetitions (or stimulus category repetitions) can occur only in those sequences in which response time benefits would mimic a conflict adaptation effect (i.e., congruent-congruent and incongruent-incongruent). Thus, we also conducted all analyses with the additional variable *Response Transition* (repetition, switch), because stimulus repetitions are restricted to response repetition trials. These analyses did not reveal a significant interaction of *Response Transition* with any of the effects of interest (F's < 2.69, p's > 0.113), while preserving the main finding (*Previous* by C*urrent Response Conflict*: F (1, 25) = 5.24, $p = .031$, $\eta_p^2 = 0.17$). This suggests that the effect was not due to stimulus priming.

3.2. Event-related potentials

3.2.1. Passive viewing

3.2.1.1. EPN

The analysis corroborated the interval and cluster selection derived from visual inspection of the EPN in the localizer task. Specifically, a highly significant result indicated that emotional (M = 2.31, SD = 1.54) as compared to neutral pictures (M = 4.37, SD = 1.56) were associated with a more negative going deflection of the surface potential (t (25) = 12.15, $p < .001$, $d_z = 2.38$; Fig. 2A).

Fig. 4. Response times as a function of the amount of conflict in the current and the previous trial. Conflict adaptation effects become apparent by a response advantage in low-as compared to high-conflict current trials when the previous trial was low in conflict, which is nullified when the previous trial was high in response conflict. Error bars represent within-subject standard errors of the mean.

3.2.1.2. LPP

Likewise, a highly significant result was also obtained for the LPP indicating relatively increased amplitudes to emotional (M = 1.18, SD = 0.94) vs. neutral (M = 0.17, SD = 0.71) pictures (t (25) = 6.49, $p < .001$, $d_z = 1.27$; Fig. 2B).

3.2.2. Emotional stroop task

3.2.2.1. N450

As compared to congruent trials (M = 3.39, SD = 2.20), incongruent current trials (M = 3.25, SD = 2.14) were associated with a relative more negative going ERP for the N450 (t (25) = 2.1, $p = .046$, $d_z = 0.41$; Fig. 3).

3.2.2.2. EPN

Analysis of the ERPs over posterior sensors in the time window of 200–300 ms yielded increased negative potentials for emotional as compared to neutral background images irrespective of the congruency of the preceding trial (Fig. 5A).

The preliminary ANOVA including only congruent and incongruent current trials confirmed that it was feasible to collapse congruent and incongruent current trials. Specifically, neither the main effect of *Current Trial Congruency* (F (1, 25) = 2.35, $p = .138$, $\eta_p^2 = 0.09$), nor the interaction of *Previous Trial Category* by *Current Trial Congruency* (F (2, 50) = 0.092, $p = .886$, $\eta_p^2 = 0.0$) reached statistical significance.

In the subsequent main analysis, it became apparent that the EPN to emotional as compared to neutral current pictures was equally sizeable across all categories of the previous trial. Accordingly, neither the interaction between *Previous Trial Category* and *Current Picture Emotionality* (F (2, 50) = 0.495, $p = .612$, $\eta_p^2 = 0.01$), nor the main effect of *Previous Trial Category* (F (2, 50) = 1.46, $p = .243$, $\eta_p^2 = 0.03$) were significant. In contrast, the main effect of *Current Picture Emotionality* (F (1, 25) = 55.2, $p < .001$, $\eta_p^2 = 0.69$) yielded a highly significant result indicating a relative negativity for emotional compared to neutral distractors.

3.2.2.3. LPP

The LPP between 400 and 700 ms also showed an emotional modulation. Specifically, emotional as compared to neutral distractor pictures were associated with a relatively more positive going deflection of the ERP. Here, however, this pattern was modulated by the category of the previous trial. Specifically, at around 400–550 ms the LPP differentiation was absent after incongruent, but not after congruent and neutral previous trials (Fig. 5B). Moreover, this observation appeared to be mostly due to a modulation of the ERPs to emotional distractors. Specifically, as compared to neutral and congruent previous trials, the amplitudes associated with emotional background pictures were reduced after incongruent previous trials (Figs. 5B–6). In addition, the topographic distribution of this effect over slightly right-lateralized centro-parietal sensor sites showed a close resemblance to the topography of the LPP as revealed in the localizer task (Figs. 2B–6).

These observations were corroborated by statistical analyses. A non-significant interaction between all variables of the preliminary three-factorial ANOVA including only congruent and incongruent current trials confirmed that congruent and incongruent trials were not differentially influenced by the category of the previous trial (F (2, 50) = 2.26, $p = .125$, $\eta_p^2 = 0.04$). In the subsequent main analysis, a significant higher-order interaction between all three variables indicated that the relation between *Previous Trial Category* and *Current Trial Emotionality* differed in early and late sections of the LPP (F (2, 50) = 6.23, $p = .004$,

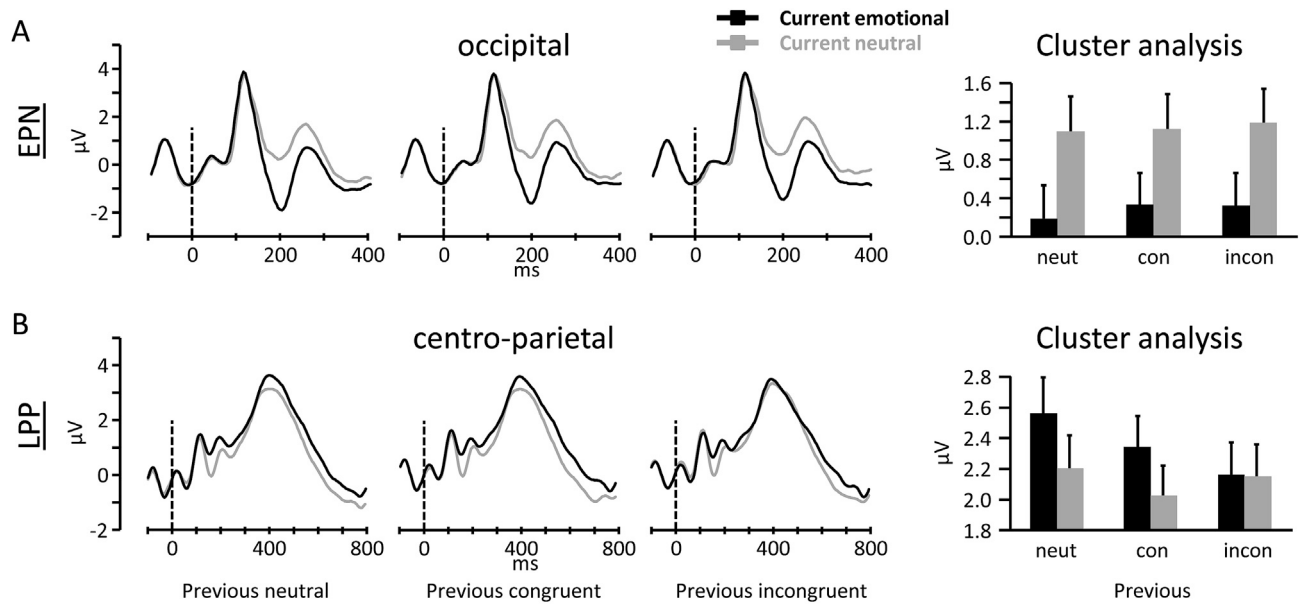


Fig. 5. Processing of emotional and neutral distractors in the Stroop task as a function of the congruency of the previous trial for the EPN (A) and the LPP (B). Event-related potentials at representative occipital (EGI# 168) and centro-parietal (EGI# 129) sensors reveal the time course of the EPN (A) and LPP (B). Bar plots in the right panel represent the mean ERPs resulting from the sensor cluster analyses in the time windows of 200–300 ms (EPN), and 400–548 ms (early LPP), respectively. Error bars represent standard errors of the mean.

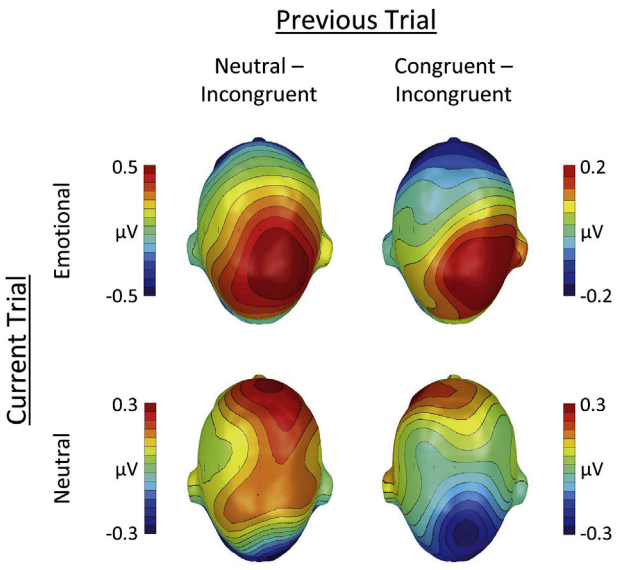


Fig. 6. Localization of the interaction effect on the early LPP. Surface plots (top view) of the difference waves [previous neutral – previous incongruent] and [previous congruent – previous incongruent] for emotional and neutral distractors in the current trial in the time window of 400–548 ms. ERPs to emotional distractors are reduced over slightly right lateralized centro-parietal sensor sites following incongruent as compared to both neutral, as well as congruent previous trials, respectively. Please note: different scales are utilized for illustrative purposes.

$\eta_p^2 = 0.1$). We thus calculated two-factorial ANOVAs including these variables separately for each time section, respectively. A highly significant interaction of both variables was obtained in the early time interval (F (2, 50) = 5.56, $p = .007$, $\eta_p^2 = 0.09$). Posthoc tests (Tukey HSD) confirmed that the LPP modulation was present after neutral ($p < .001$, $M_{emo} = 2.56$, $SD_{emo} = 1.19$, $M_{neut} = 2.20$, $SD_{neut} = 1.08$), as well as congruent trials ($p = .003$, $M_{emo} = 2.34$, $SD_{emo} = 1.03$, $M_{neut} = 2.03$, $SD_{neut} = 1.00$), but was completely abolished after incongruent previous trials ($p = .999$, $M_{emo} = 2.16$, $SD_{emo} = 1.08$, $M_{neut} = 2.15$, $SD_{neut} = 1.08$). In the later time interval, there was a significant main effect of *Current Trial Emotionality* (F (1, 25) = 26.87, $p < .001$, $\eta_p^2 = 0.52$), indicating increased amplitudes to emotional as compared to neutral background images. However, a non-significant interaction between both variables (F (2, 50) = 0.67, $p = .515$, $\eta_p^2 = 0.01$) indicated that the LPP was unaffected by the congruency of the previous trial in this time frame.

3.2.2.4. Control analyses

As with the RTs, we also explored whether these effects differed for response repetitions and switches, respectively. Again, including the variable *Response Transition* failed to yield significant interactions with the effects of interest (F's < 2.38, p's > 0.107) while preserving the main finding (*Previous Trial Category* by *Current Trial Emotionality*: F (2, 50) = 5.49, $p = .008$, $\eta_p^2 = 0.09$).

In an additional control analysis, we determined whether post-conflict effects on the early LPP differed as a function of the valence of both the target words (SEX vs. TOD), as well as the distractor images (erotic vs. mutilation; while excluding neutral images) of the current trial, respectively. This was not the case, as no significant interaction involving *Previous Trial Category* was found, neither for *Target Valence*, nor for *Distractor Valence* (F's < 0.61, p's > 0.54). This shows that control mechanisms invoked by the category of the previous trial exerted their impact on the processing of the current trial irrespective of the specific emotional valence of either the target words, or the distractor images, respectively.

Drawing strong conclusions about the temporal specificity of cognitive control rests upon directly comparing its effects on various processing stages. In a further analysis, we thus tested whether the divergence of results for the EPN and the LPP would be supported by statistical analysis. To this end, we entered the data into repeated-measures ANOVA with the variables *Previous Trial Category, Current Trial Emotionality* and *ERP Component* (EPN vs. LPP). A significant three-way interaction confirmed that adaptive cognitive control modulated the two ERP components differentially (F (2, 50) = 4.05, $p = .023$, $\eta_p^2 = 0.07$).

Finally, we also explored whether ERP responses changed during the course of the experiment. For this purpose, we split the dataset in two

equally sized halves and conducted our main ERP analyses with the additional variable of *Blocks* (1st half vs. 2nd half). This failed to reveal significant interactions with any of the effects of interest (F's < 1.18, *p*'s > 0.28) while again preserving the main finding (*Previous Trial Category* by *Current Trial Emotionality: F* (2, 50) = 7.41, $p = .002$, $\eta_p^2 = 0.11$). This clearly shows that the early LPP response was consistent across the course of the experiment, both in terms of emotional processing, as well as in terms of adaptive cognitive control effects. In contrast, there was an interaction between *Blocks* and *Current Trial Emotionality* (*F* (1, 25) = 4.68, $p = .040$, $\eta_p^2 = 0.16$) for the late LPP. Follow-up posthoc testing (Tukey HSD) revealed that the late LPP differentiated between emotional and neutral distractor pictures both during the first ($p < .001$; $M_{emo} = 0.68$, $SD_{emo} = 0.86$, $M_{neut} = 0.16$, $SD_{neut} = 0.92$), and, somewhat less pronounced, also during the second half of the experiment ($p = .012$; $M_{emo} = 0.57$, $SD_{emo} = 0.81$, $M_{neut} = 0.23$, $SD_{neut} = 0.92$).

4. Discussion

Employing an emotional Stroop task, the present study examined the impact of adaptive control mechanisms on emotional distractor picture processing. The main finding is that the detection of conflict affected the processing of emotional images in the subsequent trial. Specifically, higher LPP amplitudes to emotional vs neutral pictures were observed after low-conflict but not after high-conflict previous trials. These adaptation effects were specific to relatively later processing stages, as the EPN was unaffected by previous conflict. These data provide first evidence that conflict adaptation mechanisms attenuate the preferential processing of emotional stimuli selectively during later stages of perceptual categorization.

Behavioral and electrophysiological measures point towards conflict adaptation mechanisms underlying these effects. Behaviorally, high conflict in the current trial led to increased RTs after low-conflict but not after high-conflict previous trials. Replicating previous research (Egner et al., 2008; Etkin et al., 2006; Steinhauser et al., 2016), this suggests that emotion-mediated conflict control mechanisms were invoked to optimize behavioral performance. This interpretation also converges with the results of the N450 analysis. Here, the ERP featured a relatively negative going deflection for incongruent as compared to congruent stimuli, comparable in time course and topography to congruency effects reported previously (Folstein and van Petten, 2008). Together, these observations indicate that the brain detected and behaviorally adapted to varying stimulus congruency in the present task.

The LPP result pattern is predicted by conflict monitoring theory, which assumes that the brain possesses automatic processing routines detecting conditions of conflict and exerting adaptive control processes, optimizing subsequent task performance (Botvinick et al., 2001; Ullsperger et al., 2014). We accordingly hypothesized that conflict conditions lead to adjustments in the allocation of processing resources and the prioritization of task-relevant stimuli. Consequently, less processing resources remain available for distractor processing, thereby interfering with the automatic prioritization of emotional images. The observed LPP fully corresponds to the predicted pattern of reduced emotional sensitivity subsequent to high-conflict trials, demonstrating trial-by-trial adjustments in the processing of task-irrelevant emotional distractor stimuli (Banich et al., 2019). In contrast, as in previous studies (Flaisch et al., 2008b; Schupp et al., 2006) and during passive viewing, the LPP was larger to emotional than neutral stimuli in the absence of interfering explicit processing goals. In general, attentive processing of emotionally significant stimuli is beneficial to survival and self-preservation. The present results show, however, that this emotional default-processing mode can be regulated by top-down processes in a highly flexible fashion when interfering with explicit task goals.

The observation of attenuated emotion perception following incongruent trials is consistent with recent studies showing decreased emotional responding in situations of heightened executive control. For instance, in flanker tasks behavioral and pupillary responses exhibit reduced interference by emotional cues following incongruent trials (Cohen et al., 2011, 2015; Kalanthroff et al., 2013). In addition, activity in prefrontal areas regulating top-down cognitive control is associated with reduced perceptual processing of task-irrelevant emotional pictures (Banich et al., 2019). Neurally, the present results relate to these findings, as the LPP has been associated with increased BOLD-activity in extended networks including prefrontal cortex and amygdala (Liu et al., 2012; Sabatinelli et al., 2007, 2013). These structures provide modulatory input to emotion-sensitive regions being dynamically regulated by top-down control, including extra-striate visual cortex (Banich et al., 2019; Steinhauser et al., 2016), amygdala (Etkin et al., 2006) and brainstem structures (Cohen et al., 2015). Overall, the present results corroborate and extend existing research by highlighting the brain's ability to subdue the automatic prioritization of emotional stimuli in situations of heightened cognitive control.

Previous studies showed that the LPP is subject to interference by concurrent processing goals (Cesarei et al., 2009; Schindler and Kissler, 2016; Schupp et al., 2007a, 2014; Wiens et al., 2012). For instance, the LPP differentiation to emotional stimuli presented in the periphery or the background is abolished when participants perform a task to centrally presented stimuli (Cesarei et al., 2009; Schupp et al., 2014). Noteworthy, the present study is consistent with these findings, i.e., the LPP-amplitude difference between emotional and neutral stimuli was considerably larger during passive viewing than in the Stroop task ($\Delta M = 1.01\ \mu V$ vs. $\Delta M = 0.37\ \mu V$, $t\ (25) = 4.61$, $p < .001$, $d_z = 0.9$; Figs. 2 and 5). These interference effects presumably reflect top-down regulation processes that make the target category salient to facilitate categorical recognition and decision processes and to focus processing resources to the location where task-relevant stimuli are presented. However, these findings go beyond existing research by showing a phasic, trial-by-trial top-down regulation of processing resources by conflict monitoring processes. As in previous research (Egner et al., 2008; Etkin et al., 2006), conflict resides within the emotional domain as the present task asked for the categorization of emotional words.

These findings provide insights into the temporal unfolding of adaptive control processes. Specifically, the EPN, which precedes the LPP in time, differentiated between emotional and neutral distractors irrespective of high or low conflict in the previous trial. Thus, adaptive control was not imposed upon emotion perception in ubiquitous fashion, but selectively operated at relatively later processing stages. Cognitive models of object recognition entail the notion of separated processing stages. While early processes foster fleeting recognition and categorization, later ones allow for stimulus consolidation during a second stage subserving conscious recognition and elaborate processing of significant stimuli (Chun and Potter, 1995). Under this perspective, interference by concurrent cognitive processing may affect early and late processing stages, respectively. In fact, the EPN may be decreased when participants perform an explicit task diverting attention away from the emotional picture, thereby increasing task load and intra-modal competition for processing resources (Schupp et al., 2007a, 2014). Of note, such interference effects were also apparent in the present study. As with the LPP, EPN amplitude differences between emotional and neutral pictures were considerably larger in the passive as compared to the Stroop task condition ($\Delta M = 2.06\ \mu V$ vs. $\Delta M = 0.85\ \mu V$, $t\ (25) = 10.89$, $p < .001$, $d_z = 2.14$). Thus, our results indicate competition for processing resources between explicit task and implicit emotion processing for early and later processing stages. This, however, contrasts with the locus of impact of adaptive control processes, which subdued preferential emotion processing exclusively on later stages. This suggests varying mechanisms underlying the top-down modulation of emotion perception due to resource competition on the one hand, and conflict monitoring on the other hand. Overall, the present results establish emotional conflict adaptation as a further top-down mechanism acting upon LPP-related processes (Hajcak et al., 2010).

The present results relate to a recent fMRI study reporting comparable conflict adaptation effects in extrastriate, but not primary visual cortex

(Steinhauser et al., 2016). Both studies provide converging evidence that conflict resolution mechanisms selectively act upon relatively later stages of stimulus encoding. Comparing these results regarding the underlying functional and physiological processes, however, is difficult. Source localization and correlational fMRI analyses consistently identified EPN sources in extrastriate, but not primary visual cortex (Sabatinelli et al., 2007, 2013; Schonwald and Muller, 2014). While LPP sources are also located within extrastriate areas, they additionally extend to prefrontal cortex and limbic structures, including anterior cingulate cortex and amygdala (Liu et al., 2012; Sabatinelli et al., 2007, 2013). In the sense that these networks provide re-entrant modulatory input to extrastriate cortex potentially subserving the implementation of top-down cognitive control on emotion perception (Amaral et al., 1992; Banich et al., 2019; Etkin et al., 2006; Liu et al., 2012), the present LPP observations likely correspond to the findings of the Steinhauser et al. (2016) study. However, fMRI measures are insensitive to the transient nature of the adaptation effect as observed here. Therefore, the present results provide first evidence that the implementation of cognitive control on emotional stimulus processing is executed in selective fashion and contribute distinct information highly relevant to the understanding of the neural mechanisms underlying emotional conflict resolution.

In sum, the present results show that cognitive control elicited by the occurrence of emotional conflict optimizes future behavior by modulating the preferential processing of emotional stimuli. In addition, top-down control is exerted in temporally and functionally selective fashion, exclusively acting upon later encoding stages subserving conscious recognition and elaborate stimulus processing. These data support the idea of conflict monitoring as a pivotal mechanism for the allocation of cognitive control (Botvinick et al., 2001) and demonstrate that the interplay of conflict adaptation and preferential emotion processing is not ubiquitous but needs to be detailed at each stage of stimulus encoding separately.

Competing interests

The authors declare no competing financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.06.040.

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