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Electrophysiological evidence for flexible adjustments in cognitive control depending on feedback's contingency

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ABSTRACT

Cognitive control is a fundamental ability that enables to detect and resolve conflict. However, this ability is not encapsulated but liable to learning and motivational factors. Among them, previous studies have shown that the contingency created between conflict and performance by means of feedback, as well as its actual motivational value, influenced the behavioral manifestations of cognitive control. In this EEG study, we sought to shed light on the brain mechanisms underlying this modulation. To this end, fifty-eight participants performed the confound-minimized Stroop task wherein either congruent (i.e., no-conflict) or incongruent trials (i.e., conflict) were selectively reinforced by a performance feedback at the block level. Moreover, this feedback was either negative or neutral. At the behavioral results, we replicated previous results showing that conflict adaptation slightly improved when congruent trials were reinforced, while the reinforcement of incongruent trials led to a reduction of the congruency effect instead. Interestingly, at the EEG level, we found that this dissociation was captured by different event-related potentials (ERPs, as well as frontal alpha), but not mid-frontal theta (MFT), which was increased by conflict and performance feedback throughout. When incongruent trials were reinforced by the feedback, mostly the stimulus-locked N450 and the preceding occipital P1 component changed. In comparison, when congruent trials were selectively reinforced, the feedback-locked P3 component was altered. These findings suggest that depending on the specific contingency created between conflict and performance feedback, either stimulus or feedback-locked brain processes guide the implementation of cognitive control.

1. Introduction

According to the dual mechanisms of cognitive control (Braver, 2012) and several empirical studies that have subsequently confirmed this theoretical framework, the congruency effect and the conflict adaptation effect have been linked, at least under specific circumstances, to proactive and reactive control, respectively. In this framework, these two control modes reflect two distinct, yet complementary, mechanisms, characterized by different temporal dynamics: reactive control is transient and local, while proactive control is sustained and global. In agreement with this view, several studies have linked the congruency effect to proactive or sustained control in the past, being conceived as a form of control that operates by activating and sharpening specific goal representations prior to stimulus onset (Braver, 2012; Bräutigam et al., 2024; Bugg & Smallwood, 2016; Gonthier et al., 2016; Unsworth & Miller, 2023). Moreover, in several other ones, the conflict adaptation effect was regarded as a temporary and phasic enhancement of cognitive control, which was compatible with reactive control (Akçay & Hazeltine, 2011; Alpay et al., 2009; Botvinick et al., 2001; Egner et al., 2010; Funes et al., 2010; Scherbaum et al., 2011; Verguts & Notebaert, 2008). As a matter of fact, in a default situation where congruent and incongruent trials are randomly presented and equally likely, the congruency effect and the conflict adaptation effect can be explained using this framework. In addition, following the influential conflict-monitoring theory, cognitive control can be reactively enhanced following conflict processing (Blais et al., 2007; Botvinick et al., 2001) and this reactive effect underlying conflict adaptation is believed to be mostly transient and used as the default control mode.

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However, some studies have also reported results that do not lend support to this assumption (and theoretical model), for example by showing a role of proactive or sustained control in conflict adaptation. For instance, when a valid cue informs participants about the (congruency of the) upcoming trial or when the proportion of incongruent trials increases within a block, this behavioral effect seems to be driven by a proactive control component (Duthoo et al., 2014). In addition, reactive control and proactive control are not independent from each other, but likely complementing each other instead. These two mechanisms can be flexibly engaged depending on the actual task demands and contextual factors, with the optimal control mode being set depending on them and that could reflect a blend of proactive or reactive control (Yamaguchi & Nishimura, 2019). More specifically, several previous behavioral studies found that increasing the proportion of incongruent trials at the list-level or the presentation of a valid cue both led to a shift from reactive to proactive control (Braver et al., 2021; Duthoo et al., 2014; Gonthier et al., 2016; Spinelli & Lupker, 2022). Moreover, reward prospect was shown to reduce the congruency effect in both RTs and conflict-related ERP components (Kang et al., 2019), likely reflecting enhanced proactive control in this situation. Thus, specific manipulations influencing the congruency effect have been associated with shifts toward proactive control. That is, under certain conditions, the magnitude of the congruency effect has been shown to reflect the extent of anticipatory or sustained engagement of control (Bräutigam et al., 2024; Bugg & Smallwood, 2016; Gonthier et al., 2016; Unsworth & Miller, 2023). In these situations and with these manipulations, the congruency effect tends to be reduced due to a better preparation for the upcoming conflict. On the other hand, the conflict adaptation effect is widely interpreted as reflecting reactive control (Egner & Ely, 2010). Hence, at both the empirical and theoretical levels, there is some evidence for linking the congruency effect to proactive control while the conflict adaptation effect would reflect reactive control instead.

Moreover, performance feedback provides participants with an important signal to foster cognitive control, especially when conflict tasks are used (Bugg et al., 2015; Chiew & Braver, 2016; Kostandyan et al., 2019; Soutschek et al., 2014, 2015), enabling them in turn to flexibly adjust it according to the current goal and task demands (Braver et al., 2014; Kok, 2022). However, what feature is reinforced by the performance feedback during conflict tasks presumably determines how cognitive control can eventually operate and unfold. Because cognitive control is recruited to deal with conflict (Botvinick et al., 2004; Egner, 2008), if the performance feedback informs about the efficacy of conflict processing and resolution (i.e., it is linked to conflict trials), then it is suggested to promote a distinct cognitive control mode or state compared to the reinforcement of non-conflict trials, considering that expected reward and perceived efficacy can jointly influence the implementation of effortful cognitive control (Frömer et al., 2021; Shenhav et al., 2021; Silvestrini et al., 2022). In addition, if this performance feedback has an enhanced motivational value, for example it is either reward or punishment-related, this dissociation should be exacerbated (Wirth et al., 2016). According to this framework, the congruency effect and the conflict adaptation effect should therefore change depending on the specific contingency created between performance feedback and congruency (i.e., conflict vs. non-conflict), as well as the motivational significance of the former. In other words, feedback contingency should determine how cognitive control is used and implemented by the participants. From the perspective of associative learning (Abrahamse et al., 2016), cognitive control and learning are closely related to one another and accordingly, the former process varies depending on which feature or element is reinforced selectively (Chiu et al., 2017; Jiang et al., 2015).

Evidence for this framework mostly comes from behavioral studies that have reported changes of conflict adaptation (but also the congruency effect to a lesser degree) not only depending on the motivational significance of the performance feedback delivered (Braem et al., 2012; Yang & Pourtois, 2018; Yee et al., 2022) or conflict's probability encountered at the block level (e.g., the list-wide proportion congruency effect, see Braver et al., 2021; Gonthier et al., 2016; Spinelli & Lupker, 2022), but also the specific contingency created between this feedback and conflict (Chen et al., 2021; Prével et al., 2021; Yang et al., 2022). For example, in a recent study (Yang et al., 2022), we used the confound-minimized Stroop task (Braem et al., 2019) in a large group of participants (n = 53) and compared the size of the congruency effect as well as the adaptation effect when the performance feedback was coupled with either congruent (non-conflict) or incongruent (conflict) trials in separated blocks. Moreover, in that study (Yang et al., 2022), this performance feedback could be either neural or punishment-related (i.e., monetary loss incurred upon slow or incorrect responses), with the assumption that the latter should spur cognitive control (Dignath et al., 2020; Yang & Pourtois, 2018; Yang et al., 2019). The behavioral results showed that if the performance feedback reinforced conflict processing rather than non-conflict processing, both the congruency effect and the conflict adaptation effect decreased. Hence, the selective reinforcement of conflict (incongruent trials) vs. non-conflict (congruent trials) appeared to yield a change in cognitive control. In light of the studies that have linked proactive control with the congruency effect and reactive control with the conflict adaptation effect in the past (Alpay et al., 2009; Braver, 2012; Egner et al., 2010; Funes et al., 2010), these behavioral results indirectly suggest that feedback contingency with conflict led to a gain in proactive control while if this contingency occurred with non-conflict trials, reactive control prevailed instead. Moreover, this intriguing dissociation was larger when the performance feedback was punishment-related than neutral. Similar effects have also been found previously when reward was used instead of punishment at the feedback level (Chen et al., 2021; Prével et al., 2021), suggesting that the motivational value of the feedback, rather than its valence could be important to drive these effects and hence flexibility.

Hence, the contingency created between congruency and feedback reveals that cognitive control is flexible and probably relying either on proactive control (when this feedback is used to reinforce incongruent trials) or reactive control (when it is used to reinforce congruent trials, selectively). More specifically, when conflict trials were selectively reinforced by a performance feedback at the block level, this feedback could serve as a potent 'cue' to inform them about conflict handling and resolution, especially when this information is explicitly communicated to the participants via specific instructions. However, it remains unclear through which brain mechanisms this flexibility emerges. To address this question, electroencephalography (EEG) can be harnessed because it enables to track, with a millisecond time-resolution, specific brain processes involved in conflict processing and by extension cognitive control (Cavanagh & Cohen, 2022; Cohen & Donner, 2013). More specifically, specific EEG correlates of cognitive control have been identified in the past. In the time domain, the N450 event-related brain potential (ERP) has been put forward as an important electrophysiological correlate of conflict processing (besides the N2), especially when complex tasks such as the Stroop task are used (Lansbergen et al., 2007; Rey-Mermet et al., 2019; Spronk & Jonkman, 2012). The amplitude of the N450 varies as a function of conflict processing and has been linked to the dorsal Anterior Cingulate Cortex (ACC), which is an important hub in the brain systems involved in cognitive control (Badzakova-Trajkov et al., 2009; Larson et al., 2009; Szucs & Soltész, 2012; Tillman & Wiens, 2011; West et al., 2005). Besides the N450, another stimulus-locked ERP component, namely the conflict slow potential (SP), has also been related to conflict processing and adjustments in some ERP studies in the past (Chen et al., 2011; Larson et al., 2009, 2014). In the time-frequency domain, mid-frontal theta (MFT) oscillations (4–8 Hz) have been associated with cognitive control (Cohen, 2014; Duprez et al., 2020; Sauseng et al., 2006), as they usually increase when encountering cognitive-demanding events, such as conflict compared to non-conflict trials, but also punishment compared to neutral outcome (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Cohen & Cavanagh, 2011). Moreover, pre-stimulus frontal alpha asymmetry has previously been linked to the use of proactive control (Schmid et al., 2015): when subtracting left-sided (electrode F7) from right-sided (F8) alpha power, a higher value indirectly indicates greater left-sided DLPFC activity (Amodio, 2010; Pizzagalli et al., 2005). Because the N450 and MFT are well-established EEG correlates of conflict processing, we mostly focused on them in the current study and assessed how they could change depending on performance feedback reinforcement as well as punishment. In addition, we also analyzed the conflict SP as well as frontal alpha asymmetry given their association with cognitive control and more specifically proactive control for the latter one.

To this end, we employed a procedure that was similar to our previous behavioral study (Yang et al., 2022). Conflict processing was measured using the confound-minimized Stroop task, while feedback reinforcement (i.e., it reinforced either congruent or incongruent trials) and punishment were orthogonally manipulated using a block design. Moreover, when participants were told in advance that performance feedback would be contingent on incongruent (vs. congruent) trials at the block level, as explicitly conveyed via instructions, this manipulation could serve as a contextual cue, prompting them to adopt a preparatory strategy to better handle conflict. At the behavioral level, we attempted to replicate our previous results showing that the congruency effect benefited from the selective reinforcement between the performance feedback and incongruent trials, reflecting a boost in proactive control. Presumably, in this situation, the participants would focus more on stimulus than feedback processing. Symmetrically, the selective reinforcement of congruent trials by the performance feedback improved conflict adaptation, an effect akin to a gain in reactive control. This effect would mostly be reflected by a stronger and differential feedback processing in this condition. Moreover, we surmised that this dissociation should be exacerbated by punishment, considering that it could be integrated into the active conflict-related representation, thereby amplifying the cognitive control signal responsible for handling conflict. At the EEG level, we hypothesized that the N450 would be larger for incongruent than congruent trials (Larson et al., 2009), and importantly, this amplitude difference would be smaller when proactive control would prevail (Badzakova-Trajkov et al., 2009), i.e., when conflict was reinforced by the feedback, selectively. In an exploratory analysis, we also scored and assessed the conflict SP (see Supplementary materials). With regard to MFT, we expected it to be larger for punishment compared to no-punishment, as well as for incongruent compared to congruent trials (Cavanagh & Shackman, 2015; Nigbur et al., 2011). We also investigated whether it could change depending on feedback reinforcement or not, being potentially larger when reactive control would be fostered compared to proactive control (Cooper et al., 2015, but see Mendl et al., 2024). Moreover, we surmised frontal alpha asymmetry to be larger in the proactive than reactive control condition (Schmid et al., 2015). Besides these conflict-related EEG components (i.e., N450 and MFT), we also explored whether feedback reinforcement could alter early stages of stimulus processing in the visual cortex or not. We reasoned that if proactive control prevails, then we could expect that early stages of stimulus processing could benefit from this specific control mode and eventually show a gain control effect (Egner & Hirsch, 2005; Hillyard et al., 1998), compared to reactive control. Given that the extrastriate P1 component has been associated with attention-dependent gain control effects in the past, we mostly focused on its possible modulation depending on feedback reinforcement as well as punishment. Moreover, at the feedback level, we also analyzed the feedback-related negativity (FRN, Yeung & Sanfey, 2004; see Supplementary materials), the P3 component (Nieuwenhuis et al., 2005; Olofsson et al., 2008; Severo et al., 2017), as well as MFT (Cavanagh & Shackman, 2015). Because the amplitude of the P3 increases when the motivational value of the feedback is enhanced (Polich, 2007; Sato et al., 2005; Van Den Berg et al., 2012; Yang et al., 2019; Yeung & Sanfey, 2004), we examined if it could change depending on feedback reinforcement as well as punishment. Likewise, we assessed if MFT in response to the feedback might also vary as a function of these two factors.

2. Methods

2.1. Participants

The sample size was determined a priori based on a power analysis (MorePower 6.0; Campbell & Thompson, 2012) using the effect size for the modulation of the congruency effect by feedback reinforcement reported in our previous study ($\eta_p^2 = 0.138$; see Yang et al., 2022), and where a similar design was used. It indicated that 50 participants had to be included in the sample with a power of 80 % and with the alpha level of 0.05. Fifty-eight young adults were recruited. Six were excluded from the analyses because four of them had noisy EEG data[3] while two others did not complete the task as required. The remaining fifty-two participants (mean age = 19.58 years, *SD* = 1.7, 5 males) were included in the analyses of the behavioral and EEG data. All participants were right-handed and reported no history of psychological disorders or neurological diseases, and had normal or corrected-to-normal vision. Each participant received a performance-based compensation ranging from 65 to 75 RMB (see procedure here below). This experiment was approved by the Ethical Committee of the Institute of Brain and Psychological Sciences at Sichuan Normal University.

2.2. Stimuli and task

We used a confound-minimized Stroop task controlling for effects of feature repetition and contingency learning (Schmidt & Weissman, 2014; Weissman et al., 2014). The Stroop stimuli consisted of four words (in Chinese) ("红"/red, "蓝"/blue, "绿"/green, or "黄"/yellow) presented in one out of four possible colors (red, RGB: 255, 0, 0; blue, RGB: 0, 176, 240; green, RGB: 0, 255, 0; yellow, RGB: 255, 255, 0). To rule out contingency learning, two pairs of stimulus-response rules were arbitrarily created to balance congruent and incongruent trials. Each pair consisted of two words and two corresponding colors such that incongruent trials were created for the (incompatible) word-color association within each pair, but not across pairs. According to this rule, 8 types of stimuli were created in total (instead of 16 if all combinations were constructed), corresponding to 4 stimuli for congruent trials and 4 stimuli for incongruent trials. Each word was presented equally often in the congruent and incongruent color in each block within each mapping (Mordkoff, 2012). To rule out feature repetitions across successive trials, the stimulus/word was presented in only two of the possible four colors and was systematically alternated across successive trials to ensure that there was no stimulus (or response) repetition for both goal-relevant (color) and goal-irrelevant (semantic meaning) dimensions. On each trial, participants were instructed to identify the color of the word (i.e., color naming task) as fast and accurate as possible by using four color-coded keys on a keyboard (i.e., red, blue, green, yellow). More specifically, they used their left middle finger to respond to red color, left index finger to blue color, right index finger to green color, and right middle finger to yellow color.

At the beginning of each trial, a fixation cross was presented with a mean duration of 500 ms (range: 400–600 ms), which was used as intertrial interval (ITI). The Stroop stimulus was presented in the middle of the screen for 1000 ms or until a response was given, followed by a blank screen shown for 700 ms, before either an evaluative or neutral feedback was presented for 700 ms. The adjective "evaluative" means that the feedback informed about performance. More specifically, either a

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[3] We labeled epochs as "bad" if they had more than a 100 μV step within 100 ms intervals. Poor channels were identified as those that had a "bad" label for more than 20 % of the epochs. On this basis, four participants were removed because they had more than 10 % of the channels that were identified as poor.

negative feedback (i.e., a black cross mark) was provided if the response was incorrect or too slow (i.e., slower than the response cutoff; see details here below) or a positive feedback (i.e., a black tick mark) was provided if the response was correct and fast enough (i.e., faster than the response cutoff; see Fig. 1). The neutral feedback (i.e., a black square) indicated a response had been made and registered, without specific information provided about performance, however. With regard to the response cutoff, we used an algorithm validated previously that enforces fast responding (Aarts & Pourtois, 2010; Vocat et al., 2008), and ensured a balanced proportion of positive and negative feedback on average without yielding excessive frustration.[4] The response cutoff was updated on a trial-by-trial basis. More specifically, if the previous response was correct and the RT was smaller than the cutoff, then this cutoff for the current trial was updated using the formula [RT(previous trial) + Cutoff (previous trial)]/2; if not (i.e. incorrect response and/or the RT was slower than the cutoff), it stayed the same (see screenshot here below). It is worth mentioning that this adaptive cutoff operated independently of trial congruency, as successive trial could differ along this variable. To ensure comparability in the proportion of positive and negative feedback across the two block types (i.e., FB-C vs. FB-I), we implemented a smaller initial cutoff in the FB-C condition relative to the FB-I condition. Unknown to the participants, the reaction time (RT) cutoff was updated on a trial-by-trial basis to deal with unwanted fatigue or habituation effects throughout the experimental session.

2.3. Procedure

The Feedback type (Punishment vs. No-punishment) and Feedback position (following Congruent vs. following Incongruent trials) were orthogonally manipulated at the block level. Consequently, the experiment consisted of four sessions corresponding to four different conditions: Punishment-Feedback following Congruent trials (P-FB-C, see Fig. 1A), Punishment-Feedback following Incongruent trials (P-FB-I, see Fig. 1B), No Punishment-Feedback following Congruent trials (N-FB-C, see Fig. 1C), and No Punishment-Feedback following Incongruent trials (N-FB-I, see Fig. 1D). Their order was counterbalanced across participants. For the P-FB-C and N-FB-C conditions, the performance feedback (either negative or positive) was selectively presented following congruent trials, while the neutral feedback was presented following incongruent trials. Symmetrically, for the P-FB-I and N-FB-I sessions, the performance feedback was selectively presented following incongruent trials, while the neutral feedback was presented following congruent trials. Additionally, each negative feedback received in the two punishment conditions (i.e., P-FB-C and P-FB-I) was converted to monetary loss (2 cents), whereas in the two no-punishment conditions (i.e., N-FB-C and N-FB-I), it did not lead to any monetary consequence. At the beginning of each block, the participants were encouraged to make accurate and fast responses. Moreover, they were also explicitly informed about whether the performance feedback would follow either congruent or incongruent trials; but also whether punishment would be used in the ensuing block or not.

Participants were seated in front of a 24-inch computer monitor and started with a practice session that consisted of two blocks of 18 trials each to get familiarized with the task, where punishment was not involved. Then, they performed the four experimental sessions (i.e., P-FB-C, P-FB-I, N-FB-C, N-FB-I). Each session consisted of three blocks comprising 81 trials. Self-spaced breaks were allowed in between blocks. For each block, stimuli were shown in a pseudo-random order, leading to the same number of congruent-Congruent (cC), congruent-Incongruent (cI), incongruent-Congruent (iC) and incongruent-Incongruent (iI) trials that were used offline to compute conflict adaptation (see below). Stimuli presentation and response recording were controlled using E-Prime (Version 2.0; Psychology Software Tools Inc., Sharpsburg, PA).

2.4. Subjective ratings

2.4.1. Positive and negative affect schedule (PANAS)

A Chinese version of the Positive and Negative Affect Schedule (PANAS; Qiu et al., 2009) was used to measure changes in negative affect between the four main conditions. The PANAS was administered 5 times in total (after the practice for the first time as the baseline, and after each session subsequently). The scale consists of 18 items (words) describing positive (9-item) or negative (9-item) emotions, and the participants rated the 18 items on a 5-point scale ranging from 1-Very slightly or not at all to 5-Extremely. The order of these 18 items was changed across the five measurement points to avoid the use of a specific response strategy.

2.4.2. Dislike feelings (negative feedback)

Participants were also asked to rate their dislike feelings towards the negative feedback received by means of a Visual Analog Scale (VAS) ranging from 0 (not at all) to 100 (a lot) along a putative dislike continuum. These ratings were presented for the first time after the practice session and subsequently after each session (hence, 5 times in total).

2.5. Data analysis

2.5.1. Behavioral data analysis

Data preprocessing, visualization and analysis were carried out in R (R Core Team, 2021), using the tidyverse (Wickham et al., 2019), ggplot2 (Wickham et al., 2016), and lme4 (Bates et al., 2015) packages. For each subject separately, the first trial of each block, and outlier trials (over ± 3 SD from the mean) were excluded, leading to 48789 trials kept out of 50544 trials available in total (96.5 %). Similarly for the RT data, the first trial of each block, error trials, post-error trials, and outliers were excluded from further analyses, leading to 34,138 trials kept out of 50544 trials available in total (67.5 %). RT data were analyzed using a Linear Mixed Model (LMM) with which RTs were log-transformed, and accuracy data, which are corresponding to a categorical dependent variable, were analyzed using a Generalized Linear Mixed Model (GLMM) with binomial distribution and a logit link function. We used the mean-centered deviation coding for the four factors included in the statistical analyses (Feedback type, Feedback position, Previous congruency and Current congruency).[5]

For the (G)LMMs, the intercept for each subject was added as the random effect, and four main effects, six two-way interactions, four three-way interactions, and a four-way interaction were added as the fixed effects for the models, guided by our experimental design. We started our analysis by specifying a full model to evaluate the contributions of both main effects and interaction effects. Next, we employed

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[4] The neutral feedback presented as a black square in the FB-C and FB-I conditions was also labeled either positive or negative (depending on the accuracy and RT speed) offline, eventually ensuring a balanced proportion of negative and positive feedback across conditions at the block level. However, the ratio of negative feedback received by the participants was larger in the FB-I compared to the FB-C conditions. Accordingly, we also ran a control analysis dealing with this asymmetry (see Supplementary materials).

[5] In a control analysis (see Supplementary materials), we also performed model comparisons on the behavioral data to assess whether Previous congruency (and hence conflict adaptation) accounted for the variance beyond Current congruency. To this end, we compared full models including Previous congruency (i.e., Previous congruency × Current congruency × Feedback type × Feedback position) with reduced models omitting this factor (i.e., Current congruency × Feedback type × Feedback position). The results showed that the full models provided significantly better fit for both RTs and accuracy, indicating that Previous congruency did carry explanatory value beyond that provided by Current congruency alone.

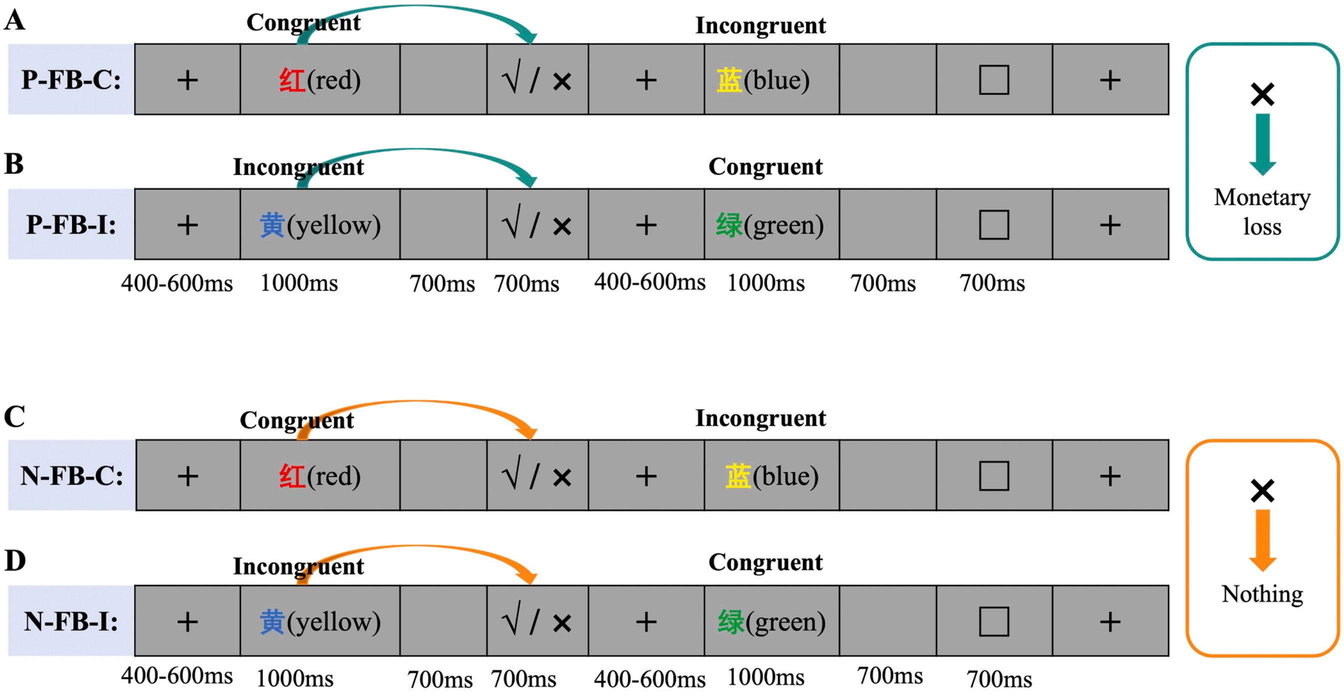

Fig. 1. Experimental procedure. Each trial started with a fixation cross that lasted 500 ms on average, followed by a Stroop stimulus. A blank screen was then presented, before either an evaluative (negative or positive) or neutral feedback selectively followed either congruent or incongruent stimuli. A. Punishment-Feedback following Congruent trials condition (P-FB-C). The evaluative feedback selectively followed congruent trials, and each negative feedback was converted to monetary loss. B. Punishment-Feedback following Incongruent trials condition (P-FB-I). The evaluative feedback selectively followed incongruent trials, and each negative feedback was converted to monetary loss. C. No punishment-Feedback following Congruent trials condition (N-FB-C). The evaluative feedback selectively followed congruent trials, and none of the negative feedbacks was converted to monetary loss. D. No punishment-Feedback following Incongruent trials condition (N-FB-I). The evaluative feedback selectively followed incongruent trials, and none of the negative feedbacks was converted to monetary loss.

likelihood ratio tests (LRT) to assess whether the exclusion of any fixed effect led to a significant reduction in model fit. This stepwise approach allowed us to determine the statistical significance of each fixed effect included in the model.

2.5.2. *Correlation analyses*

For RTs, we also computed indices of congruency and conflict adaptation (van Steenbergen et al., 2010). For the congruency effect, we subtracted congruent from incongruent trials. For conflict adaptation, we used the ([cI-cC]-[iI-iC]) formula. For each index separately, we first computed it between FB-C and FB-I conditions, and then performed statistical comparisons using paired sample t-tests. Last, we also computed bivariate correlations (using Pearson correlation coefficients) between the congruency effect and the conflict adaptation effect.

2.5.3. *Subjective ratings*

2.5.3.1. PANAS. The values of positive and negative affect were obtained from the sum of scores on positive and negative items, respectively. We also computed the internal consistency of the PANAS for each condition separately (see Supplementary materials). The resulting PANAS values were then submitted to an analysis of variance (ANOVA) with Feedback type (Punishment vs. No-punishment), Feedback position (following Congruent vs. following Incongruent trials) and Affect (Negative, Positive) as within-subject factors.

2.5.3.2. Dislike feelings (negative feedback). The mean ratings of dislike feelings for negative feedback were first computed. The resulting VAS values were then submitted to an ANOVA with Feedback type (Punishment vs. No-punishment) and Feedback position (following Congruent vs. following Incongruent trials) as within-subject factors.

2.6. *EEG data recording*

EEG was recorded using a ActiCHamp Plus system at a sampling rate of 500 Hz from 64 Ag-AgCl (silver-silver chloride) electrodes mounted in an elastic cap. The electrodes placement was made in agreement with the extended 10–20 EEG system, where FCz and AFz were used as the reference and the ground electrode, respectively. Horizontal electrooculogram (EOG) was recorded on the right side of the right eye. Electrode impedance was kept below 10 kΩ.

2.7. *EEG data analyses*[6]

The EEG was preprocessed offline with EEGLAB (Delorme & Makeig, 2004), implemented in Matlab, and included a 0.05/40 Hz high/low pass filter, re-referencing to the average of the left and right mastoids. For the ICA procedure, epoched EEG data from all channels were processed through the EEGLab's *runica* function. The ICA components pertaining to eye movements and blinks were manually removed from the data (two to three components were removed for each participant). As was done for the RTs data analyses, error and post-error trials were also removed. The EEG data were extracted from − 400 to 1000 ms

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[6] For EEG indicators that are directly related to conflict processing (i.e., N450) or indirectly (i.e., MFT), we included "Previous congruency" as a specific factor in our analyses, given that all these measures are theoretically sensitive to conflict processing (and conflict adaptation). In contrast, for the feedback-related EEG indicators (i.e., P3 and MFT at the feedback level), but also the P1 component reflecting early visual perceptual processing, we focused solely on "Current congruency". This decision was based on the assumption that these components primarily reflect responses to the immediate stimulus or feedback event, and are less likely to be modulated by the most recent trial history and hence Previous congruency.

around the stimulus onset (baseline corrected − 200 to 0 ms), and from − 700 to 700 ms around the feedback onset (baseline corrected − 200 to 0 ms). A semi-automatic artefact correction procedure was also applied to eliminate trials with voltage values exceeding ± 90 μV. Moreover, the time-frequency (TF) analysis was performed using Fieldtrip (Oostenveld et al., 2011) implemented in Matlab. More specifically, we used ‘tfr’ in the Fieldtrip toolbox (ft_freqanalysis.m, which implements wavelet TF transformation based on convolution in the time domain with seven wavelet cycles) to carry out time-frequency transforms from 1 to 30 Hz for each channel separately. As a result, the entire preprocessing procedure led to the retention of 34079 trials out of the 50544 available in total (67.4 %).[7] A baseline correction (-300 to − 100 ms pre-stimulus; − 500 to − 200 ms pre-feedback) was used. The electrode selection (see here below) was based on previous ERP studies where a similar design and data analysis were used (Yang et al., 2019; Severo et al., 2017). The time interval was determined to be within ± 50 ms around the peak value discovered in the current dataset.

2.7.1. *Conflict processing: N450 and MFT*

The N450 was quantified at Fz as the mean ERP amplitude within the 450–550 ms post-stimulus onset interval. These values were submitted to the repeated measures (rm) ANOVA with Feedback type (Punishment vs. No-punishment), Feedback position (following Congruent vs. following Incongruent trials), Previous congruency (Congruent, Incongruent), and Current congruency (Congruent, Incongruent) as within-subject factors. MFT (i.e., power in the 4–8 Hz frequency band) was extracted within the 500–900ms post-stimulus onset interval at Fz, for each subject and for each condition separately. MFT was analyzed using the same statistical model as used for the N450.

2.7.2. *Feedback processing: P3 and MFT*

The P3 was quantified at Pz as the mean ERP amplitude within 320–420 ms post-feedback onset interval; while MFT was extracted within the 200–500 ms post-feedback onset interval at Fz, for each subject and for each condition separately. Then, for each of these two electrophysiological components, a rm-ANOVA with Feedback type (Punishment vs. No-punishment), Feedback position (following Congruent vs. following Incongruent trials), and Feedback valence (Positive vs. Negative vs. Neutral) as within-subject factors was used.

For the P3, we also calculated a difference score by subtracting the ERP for the neutral feedback from that corresponding to the performance feedback (i.e., positive and negative feedback combined) and compared it, using a paired *t*-test, between the FB-C and the FB-I condition. This difference score indirectly reflects the motivational value of the feedback.

2.7.3. *Stroop stimulus processing: P1*

The P1 was quantified as the mean amplitude at PO7 and PO8 between 100 and 200 ms post-stimulus onset (Di Russo et al., 2002). These P1 amplitudes were submitted to a rm-ANOVA with Feedback type (Punishment vs. No-punishment), Feedback position (following Congruent vs. following Incongruent trials), and Current congruency (Congruent, Incongruent) as within-subject factors.

2.7.4. *Alpha power asymmetry*

An asymmetry index was computed by subtracting alpha power (8–13 Hz) measured at F7 from that at F8 between 400 ms pre-stimulus and 300 ms post-stimulus (i.e., 700 ms in total; Amodio, 2010; Pizzagalli et al., 2005; Schmid et al., 2015).[8] These values were submitted to a rm-ANOVA with Feedback type (Punishment vs. No-punishment), Feedback position (following Congruent vs. following Incongruent trials), and Current congruency (Congruent, Incongruent) as within-subject factors.

3. Results

3.1. *Behavioral data*

3.1.1. *Accuracy*

The model comparison based on the fixed effects (see Table 1) revealed a significant main effect of Feedback type, $\chi^2(1) = 6.956$, $p = .008$, with higher accuracy for punishment than no-punishment conditions. The main effect of Previous congruency was significant, $\chi^2(1) = 7.555$, $p = .006$, with higher accuracy for incongruent trials than congruent ones. The main effect of Current congruency was also significant, $\chi^2(1) = 650.590$, $p < .001$, with higher accuracy for congruent than incongruent trials. In addition, the two-way interaction between Previous congruency and Current congruency was significant, $\chi^2(1) = 24.69$, $p < .001$. It indicated that accuracy for iI trials was significantly higher than cI ones ($z = 6.128$, SE $= 0.033$, $p < .001$); whereas it did not significantly differ between cC and iC trials ($z = -1.406$, SE $= 0.040$, $p = .160$). The two-way interaction between Current congruency and Feedback position was also significant, $\chi^2(1) = 5.706$, $p = .017$. This was explained by a higher accuracy for incongruent trials in the FB-I compared to the FB-C condition ($z = 2.994$, SE $= 0.033$, $p = .003$), while this difference was not significant for congruent trials ($z = -0.634$, SE $= 0.040$, $p = .526$). Moreover, the three-way interaction between Previous congruency, Current congruency and Feedback position was significant, $\chi^2(1) = 11.578$, $p < .001$. To further explore this

Table 1
Summary of fixed effects for the analysis of the accuracy data.

Predictor	*Estimate*	*SE*	*z-value*	*Pr(> |z|)*
(Intercept)	1.867	0.099	18.823	.001***
PreCon	− 0.072	0.026	− 2.752	.006**
CurCon	0.659	0.026	25.173	.001***
FB type	− 0.069	0.026	− 2.640	.008**
FB position	− 0.036	0.026	− 1.384	.166
PreCon: CurCon	0.260	0.052	4.972	.001***
PreCon: FB type	− 0.037	0.052	− 0.698	.485
CurCon: FB type	0.052	0.052	1.002	.316
PreCon: FB position	0.081	0.052	1.540	.124
CurCon: FB position	0.125	0.052	2.391	.017*
FB type: FB position	− 0.016	0.052	− 0.296	.767
PreCon: CurCon: FB type	0.143	0.104	1.368	.171
PreCon: CurCon: FB position	0.356	0.104	3.409	.001***
PreCon: FB type: FB position	0.096	0.105	0.921	.357
CurCon: FB type: FB position	0.114	0.105	1.091	.275
PreCon: CurCon: FB type: FB position	− 0.097	0.209	− 0.465	.642

‘***’ < .001; ‘**’ < .01; ‘*’ < .05; ‘.’ < .1.

PreCon: Previous congruency; CurCon: Current congruency; FB type: Feedback type; FB position: Feedback position.

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[7] We also computed the number of trials kept for each condition and each ERP component separately (see Supplementary materials). Moreover, we also report the dependability/consistency for each ERP component and condition.

[8] In Schmid et al. (2015), the alpha asymmetry analyses were based on an ITI long enough to isolate pre-stimulus anticipatory activity. In our study, the ITI was relatively short (mean = 400 ms), preventing us to restrict them exclusively to the pre-stimulus window. For this methodological reason, we had to extend the analysis window to include both the 400 ms pre-stimulus interval as well as the 300 ms post-stimulus intervals.

interaction, two GLMMs including two factors (Previous congruency and Current congruency) were computed, for the FB-C and FB-I conditions separately. In the FB-I condition (Fig. 2A, right panel), the two-way interaction between Previous congruency and Current congruency was not significant, $\chi^2(1) = 1.285$, $p = .257$. In the FB-C condition (Fig. 2A, left panel), this interaction was significant ($\chi^2(1) = 35.657$, $p < .001$), indicating that accuracy was higher for iI than cI trials ($z = 5.484$, SE $= 0.047$, $p < .001$), while it was lower for iC compared to cC trials ($z =$ -3.244, SE $= 0.058$, $p = .001$).

Table 2
Summary of fixed effects for the analysis of RTs.

Predictor	*Estimate*	*SE*	*t-value*	*Pr (>|t|)*
(Intercept)	2.757	0.006	436.551	.001***
FB position	0.001	0.001	1.497	.134
CurCon	– 0.033	0.001	– 35.833	.001***
FB type	– 0.009	0.001	– 9.743	.001***
PreCon	– 0.008	0.001	– 8.176	.001***
FB position: CurCon	– 0.014	0.002	– 7.735	.001***
FB position: FB type	– 0.006	0.002	– 3.481	.001***
CurCon: FB type	– 0.003	0.002	– 1.658	.097.
FB position: PreCon	0.009	0.002	4.702	.001***
CurCon: PreCon	– 0.011	0.002	– 5.97	.001***
FB type: PreCon	– 0.001	0.002	– 0.407	.684
FB position: CurCon: FB type	– 0.006	0.004	– 1.526	.127
FB position: CurCon: PreCon	– 0.007	0.004	– 1.992	.046*
FB position: FB type: PreCon	– 0.002	0.004	– 0.622	.534
CurCon: FB type: PreCon	– 0.006	0.004	– 1.672	.095.
FB position: CurCon: FB type: PreCon	– 0.008	0.007	– 1.045	.296

'***' < .001; '**' < .01; '*' < .05; '.' < .1.
PreCon: Previous congruency; CurCon: Current congruency; FB type: Feedback type; FB position: Feedback position.

3.1.2. RTs

The model comparison based on the fixed effects (see Table 2) showed significant main effects of Previous ($\chi^2(1) = 66.8, p < .001$) and Current congruency ($\chi^2(1) = 1260.9, p < .001$), indicating faster RTs for congruent than incongruent trials. The main effect of Feedback type was also significant, $\chi^2(1) = 94.8$, $p < .001$, with faster RTs in the punishment than no-punishment conditions. In addition, the two-way interaction between Previous congruency and Current congruency was significant ($\chi^2(1) = 35.636$, $p < .001$), indicating conflict adaptation. The two-way interaction between Current congruency and Feedback position was also significant, $\chi^2(1) = 59.8$, $p < .001$. For incongruent trials, RTs were faster in the FB-I than in the FB-C conditions ($z =$ -6.415, SE $= 0.001, p < .001$), while for congruent trials, they were significantly slower in the FB-I than the FB-C conditions ($z = 4.333$, SE $= 0.001$, $p < .001$). Moreover, the three-way interaction between Previous congruency, Current congruency and Feedback position was also significant, $\chi^2(1) = 3.971$, $p = .046$, suggesting that conflict adaptation was modulated by Feedback position. In order to further explore this significant effect (i.e., Previous congruency × Current congruency × Feedback position), two LMMs including two factors (Previous congruency and Current congruency) were computed for the FB-C and FB-I conditions separately. In the FB-C conditions (Fig. 2B, left panel), the two-way interaction between Previous congruency and Current congruency was significant, $\chi^2(1) = 29.968$, $p < .001$. RTs were significantly faster for iI than cI trials ($z =$ -2.346, SE $= 0.002$, $p = .019$), and were also significantly faster for cC than iC trials ($z = 5.490$, SE $= 0.002$, $p < .001$). In the FB-I conditions, the two factors also significantly interacted with each other ($\chi^2(1) = 8.274$, $p = .004$; see Fig. 2B, right panel), indicating slower RTs for iI than cI trials ($z = 4.243$, SE $= 0.002$, $p < .001$), and also slower RTs for iC than cC trials ($z = 8.649$, SE $= 0.002$, $p < .001$). The four-way interaction between Previous

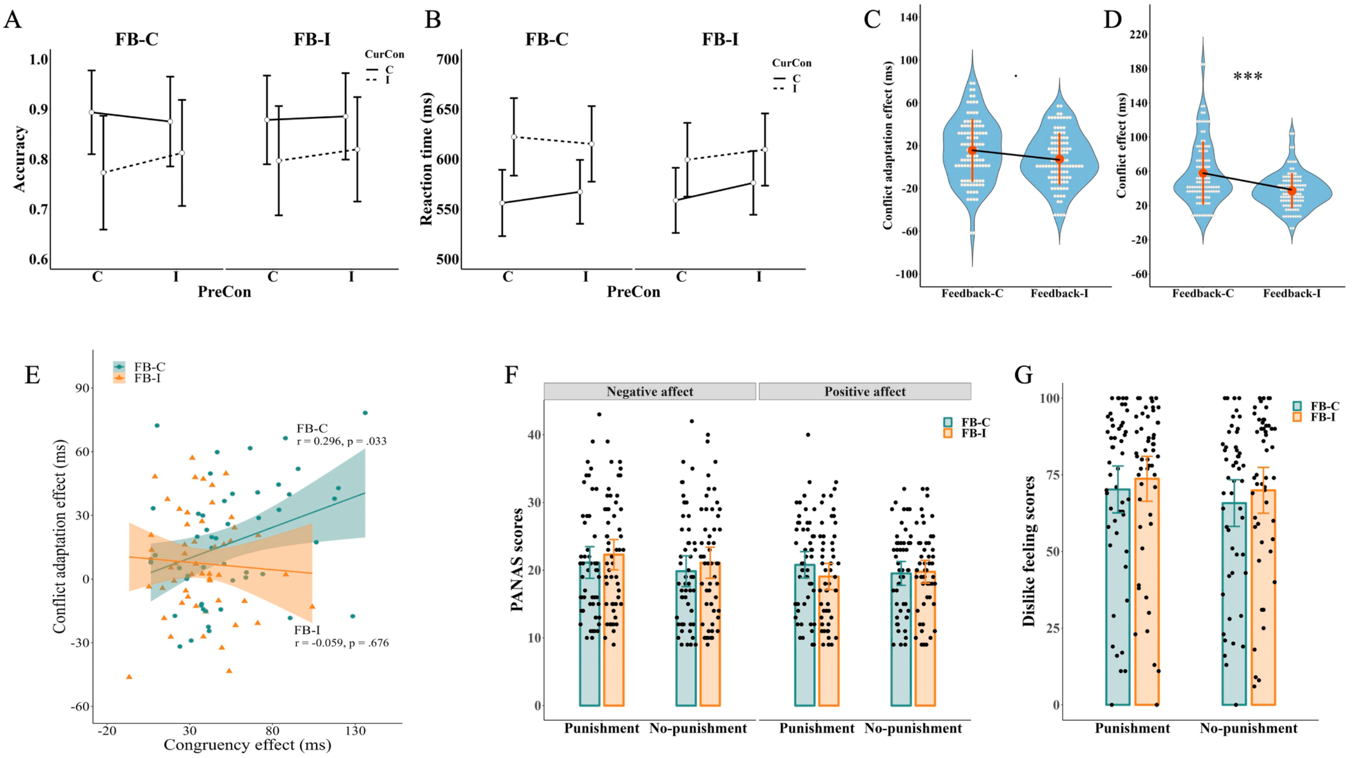

Fig. 2. **A–B.** Behavioral results. Conflict adaptation was present in the FB-C conditions, but was absent in the FB-I conditions for both accuracy (A) and RTs (B). **C.** Conflict adaptation was larger for the FB-C compared to the FB-I conditions. **D.** The congruency effect was lower for the FB-I compared to the FB-C conditions. **E.** Correlation between the congruency effect and the conflict adaptation effect for the FB-C and the FB-I conditions, separately. **F.** PANAS results. Negative affect was significantly higher in the FB-I than FB-C conditions; no such difference was observed for positive affect. **G.** Dislike ratings of negative feedback were significantly higher in the Punishment than the No punishment conditions, and moreover, they were also significantly higher for the FB-I than FB-C conditions. Vertical bars correspond to standard errors of the mean; small black or green dot and small orange triangles represent individual data. ".": $p < 0.1$, "***": $p < 0.001$.

congruency, Current congruency, Feedback type and Feedback position was not significant, $\chi^2(1) = 1.092$, $p = .296$.

3.1.3. Correlation analyses

The congruency effect was significantly lower for the FB-I ($M = 37.125$, $SEM = 2.881$) compared to the FB-C conditions ($M = 57.855$, $SEM = 5.174$), $t = -5.024$, $p = .001$ (Fig. 2D). In comparison, conflict adaptation was higher, albeit trend significant only, for the FB-C ($M = 15.630$, $SEM = 4.110$) compared to the FB-I conditions ($M = 7.394$, $SEM = 3.411$), $t = 1.828$, $p = .073$ (Fig. 2C). Moreover, in the FB-C conditions, the congruency and adaptation effect correlated positively with each other ($r = 0.296$, $p = .033$), while this correlation was not significant in the FB-I conditions (see Fig. 2E).

3.2. Subjective ratings

3.2.1. PANAS

The ANOVA showed a significant main effect of Feedback type, $F(1, 51) = 6.205$, $p = .016$, $\eta^2 = 0.108$, with higher subjective ratings for the punishment ($M = 20.82$, $SEM = 0.76$) than the no-punishment conditions ($M = 20.06$, $SEM = 0.72$). The two-way interaction effect between Feedback position and Affect was significant, $F(1,51) = 10.185$, $p = .002$, $\eta^2 = 0.166$. It indicated higher levels of negative affect when the performance feedback followed incongruent trials ($M = 21.69$, $SEM = 1.08$) compared to congruent trials ($M = 20.49$, $SEM = 1.11$), $t(51) = 3.052$, $p = .018$, 95 % CI [0.142, 2.262] (Fig. 2F, left panel), while for positive affect, this difference was not significant (Fig. 2F, right panel), $t(51) = 1.880$, $p = .315$, 95 %CI [-0.320,1.801]. No any other effect was significant, $Fs \leq 2.140$, $ps \geq 0.150$.

3.2.2. Dislike feelings (negative feedback)

The ANOVA showed a significant main effect of Feedback type, $F(1, 51) = 5.726$, $p = .020$, $\eta^2 = 0.101$, with higher dislike feelings for the punishment ($M = 71.97$, $SEM = 3.49$) than the no-punishment conditions ($M = 67.86$, $SEM = 3.56$). The main effect of Feedback position was also significant, $F(1, 51) = 6.907$, $p = 0.011$, $\eta^2 = 0.119$, with higher dislike feelings in the FB-I ($M = 71.83$, $SEM = 3.37$) than the FB-C conditions ($M = 68.01$, $SEM = 3.61$) (see Fig. 2G). However, their interaction was not significant, $F(1, 51) = 0.027$, $p = 0.871$.

3.3. EEG results

3.3.1. Conflict processing

3.3.1.1. N450.

The rm-ANOVA revealed a significant main effect of Current congruency, $F(1, 51) = 5.100$, $p = .028$, $\eta^2 = 0.091$, with larger (more negative) amplitudes for incongruent ($M = -5.781$ μV, $SEM = 3.243$) than congruent trials ($M = -5.141$ μV, $SEM = 3.162$). In addition, the two-way interaction between Feedback position and Current congruency was significant, $F(1, 51) = 9.741$, $p = .003$, $\eta^2 = 0.160$, indicating that in the FB-C conditions (see Fig. 3A–B), the N450 amplitudes were significantly larger for incongruent ($M = -5.299$ μV, $SEM = 3.191$) than congruent trials ($M = -4.082$ μV, $SEM = 3.088$; $t = -3.596$, $p = .003$, 95 %CI [-2.132, $-$ 0.304]), while this difference was not observed in the FB-I conditions (see Fig. 3A–B; $t = -0.187$, $p = .852$, 95 %CI [-0.978, $-$ 0.339]). No any other effect was significant, $Fs \leq 3.158$, $ps \geq .082$.

3.3.1.2. MFT.

The rm-ANOVA showed a significant main effect of Current congruency, $F(1, 51) = 10.881$, $p = .001$, $\eta^2 = 0.176$, with a larger MFT power for incongruent ($M = 4.112$ dB, $SEM = 0.302$) than congruent trials ($M = 3.843$ dB, $SEM = 0.330$; see Fig. 3C–D). All other effects remained non-significant, $Fs \leq 2.099$, $ps \geq .154$.

3.3.2. Stroop stimulus processing: P1

The rm-ANOVA revealed a significant main effect of Feedback position, $F(1, 51) = 4.276$, $p = .044$, $\eta^2 = 0.077$, with larger P1 amplitudes in the FB-I ($M = -1.223$ μV, $SEM = 0.297$) than the FB-C conditions ($M = -1.037$ μV, $SEM = 0.301$) (Fig. 3E–F). No any other effect reached significance, $Fs \leq 1.825$, $ps \geq .183$.

3.3.3. Feedback processing

3.3.3.1. P3.

The rm-ANOVA showed a significant main effect of Feedback type, $F(1, 51) = 8.902$, $p = .004$, $\eta_p^2 = 0.149$, with larger (more positive) amplitudes for the punishment ($M = 6.133$ μV, $SEM = 0.677$) than the no-punishment conditions ($M = 5.337$ μV, $SEM = 0.648$). The main effect of Feedback valence was also significant, $F(1.791, 91.357) = 71.131$, $p < .001$, $\eta^2 = 0.582$. Post hoc comparisons showed that the P3 amplitudes were significantly larger for the positive ($M = 8.519$ μV, SEM = 0.742) than either the negative (M = 6.826 μV, SEM = 0.754) or the neutral feedback ($M = 1.861$ μV, $SEM = 0.693$; $ts \geq 2.918$, $ps \leq .004$). Moreover, the P3 amplitudes for the negative feedback were also significantly larger than the neutral feedback ($t = 8.556$, $p < .001$). The two-way interaction between Feedback valence and Feedback type was significant, $F(2, 102) = 6.675$, $p = .002$, $\eta^2 = 0.116$, indicating that the P3 amplitudes for negative feedback in the punishment conditions ($M = 7.565$ μV, $SEM = 0.810$) were significantly larger than that in the no-punishment conditions ($M = 5.995$ μV, $SEM = 0.736$; t = 4.652, $p < .001$, 95 %CI [0.592, 2.730]), while this difference was not observed for either the positive or the neutral feedback ($ts \leq 0.876$, $ps \geq .742$). In addition, the two-way interaction between Feedback valence and Feedback position was significant, $F(1.778, 90.697) = 3.387$, $p = .044$, $\eta^2 = 0.062$. This effect was explained by larger P3 amplitudes for positive feedback ($M = 9.017$ μV, $SEM = 0.748$) compared to negative feedback ($M = 7.236$ μV, $SEM = 0.797$) in the FB-C conditions (see Fig. 4A–B; $t = 2.770$, $p = .038$, 95 % CI [-0.138, 3.699]), while this difference was not significant in the FB-I conditions (see Fig. 4C–D; $t = 2.498$, $p = .068$). Moreover, when using difference scores for the P3, the results showed a larger value in the FB-C (M = 6.431 μV, $SEM = 0.688$) compared to the FB-I conditions (M = 5.192 μV, $SEM = 0.570$), $t = 2.259$, $p = .028$, 95 % CI [0.138, 2.340] (see Fig. 4E).

To further explore whether the larger ratio of negative feedback in the FB-I than FB-C condition might influence the P3, we made the proportion of negative feedback comparable in the FB-I and FB-C conditions by randomly subsampling epochs in the former condition. Then, we reanalyzed at the statistical level the P3 component. Importantly, the two-way interaction between Feedback valence and Feedback position was marginally significant ($F(2, 102) = 2.960$, $p = .056$, $\eta^2 = 0.055$) and it showed the same effects as the analysis run when we did not control for this slight asymmetry (see Supplementary materials).

3.3.3.2. MFT.

The rm-ANOVA showed a significant main effect of Feedback valence, $F(1.744, 88.950) = 27.408$, $p < .001$, $\eta^2 = 0.350$. The MFT power was significantly larger for negative ($M = 0.633$ dB, $SEM = 0.171$) compared to either positive (M = 0.347 dB, $SEM = 0.162$) or neutral ($M = -0.259$ dB, $SEM = 0.162$) feedback ($ts \geq 2.328$, $ps \leq .022$). In addition, the two-way interaction between Feedback valence and Feedback position was significant (see Fig. 5C), $F(2, 102) = 15.716$, $p < .001$, $\eta^2 = 0.236$. The MFT power for performance feedback (positive and negative) was larger in the FB-C (Fig. 5A) than the FB-I (Fig. 5B) conditions ($ts \geq 2.905$, $ps \leq .026$), whereas it was smaller in the FB-C than the FB-I conditions for neutral feedback ($t = 2.615$, $p = .050$).

3.3.4. Alpha power asymmetry

The rm-ANOVA revealed a significant main effect of Feedback position, $F(1, 51) = 4.406$, $p = .041$, $\eta^2 = 0.080$, with a higher value in the FB-I ($M = 0.015$ μV, $SEM = 0.025$) than the FB-C conditions ($M = -0.046$ μV, $SEM = 0.030$) (Fig. 3G–H). No any other effect reached

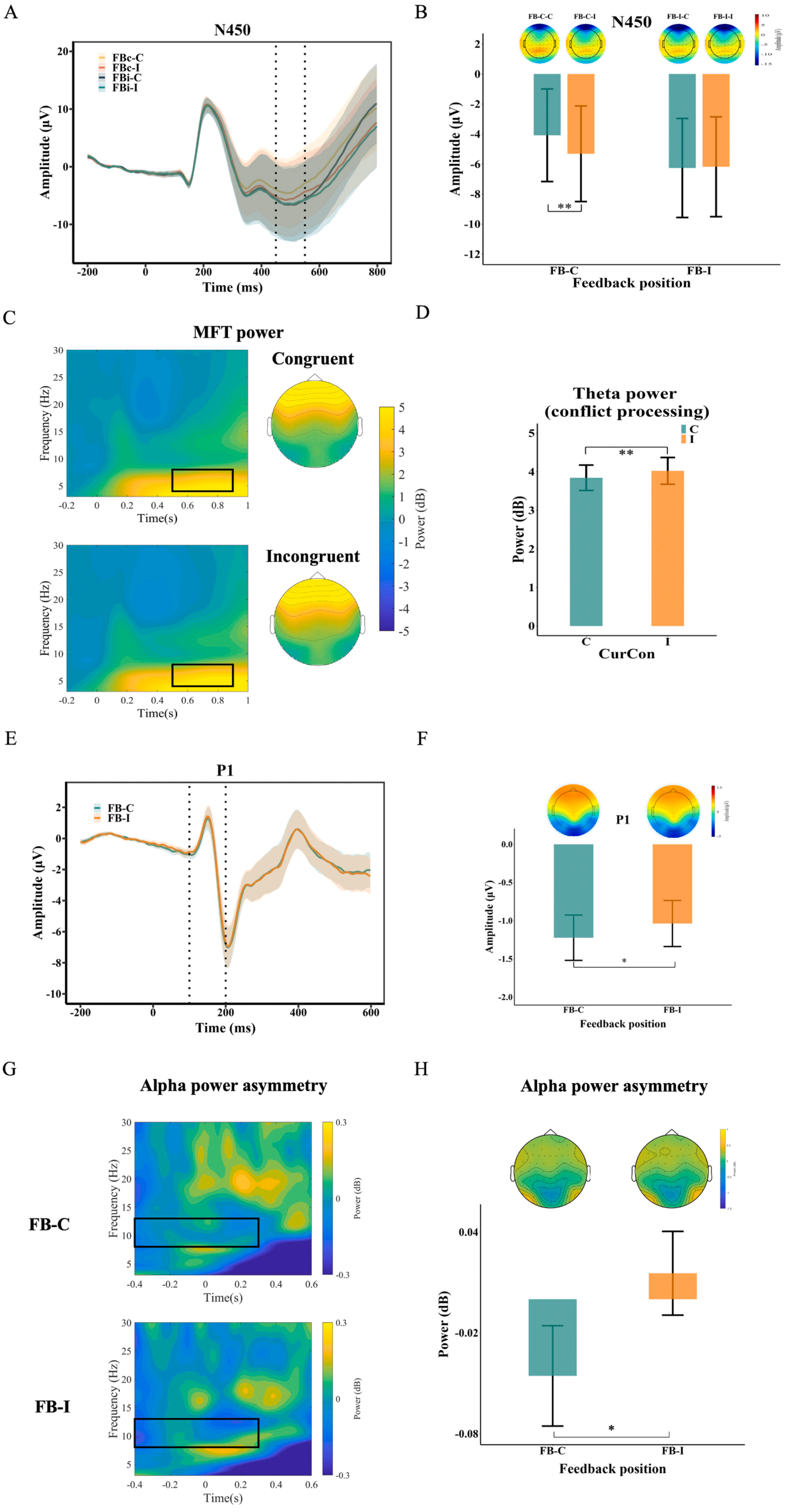

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Fig. 3. Stimulus processing EEG results. A. N450 results. Grand average ERP waveforms from Fz. B. Mean amplitude of the N450 (extracted in the 450–550 ms interval following stimulus onset) and horizontal topographical maps for the four main conditions (i.e., FB-C-C, FB-C-I, FB-I-C, FB-I-I), separately. C. MFT (4–8 Hz) power and horizontal topographical maps for congruent and incongruent trials. D. MFT power was significantly larger for incongruent relative to congruent stimuli. E. P1 results. Grand average ERP waveforms from electrodes PO7 and PO8 (pooled together). F. Mean P1 amplitudes and horizontal topographical map for the FB-C and FB-I conditions, separately. G. Time-frequency decomposition at F8-F7, separately for the FB-C and FB-I conditions. The superimposed rectangle represents alpha (8–13 Hz) and the time interval used to compute mean power of this frequency band. H. A larger frontal alpha power asymmetry was found in the FB-I than FB-C conditions. The horizontal topographical map for alpha (8–13 Hz) is shown. “**”: $p < 0.01$, “*”: $p < 0.05$.

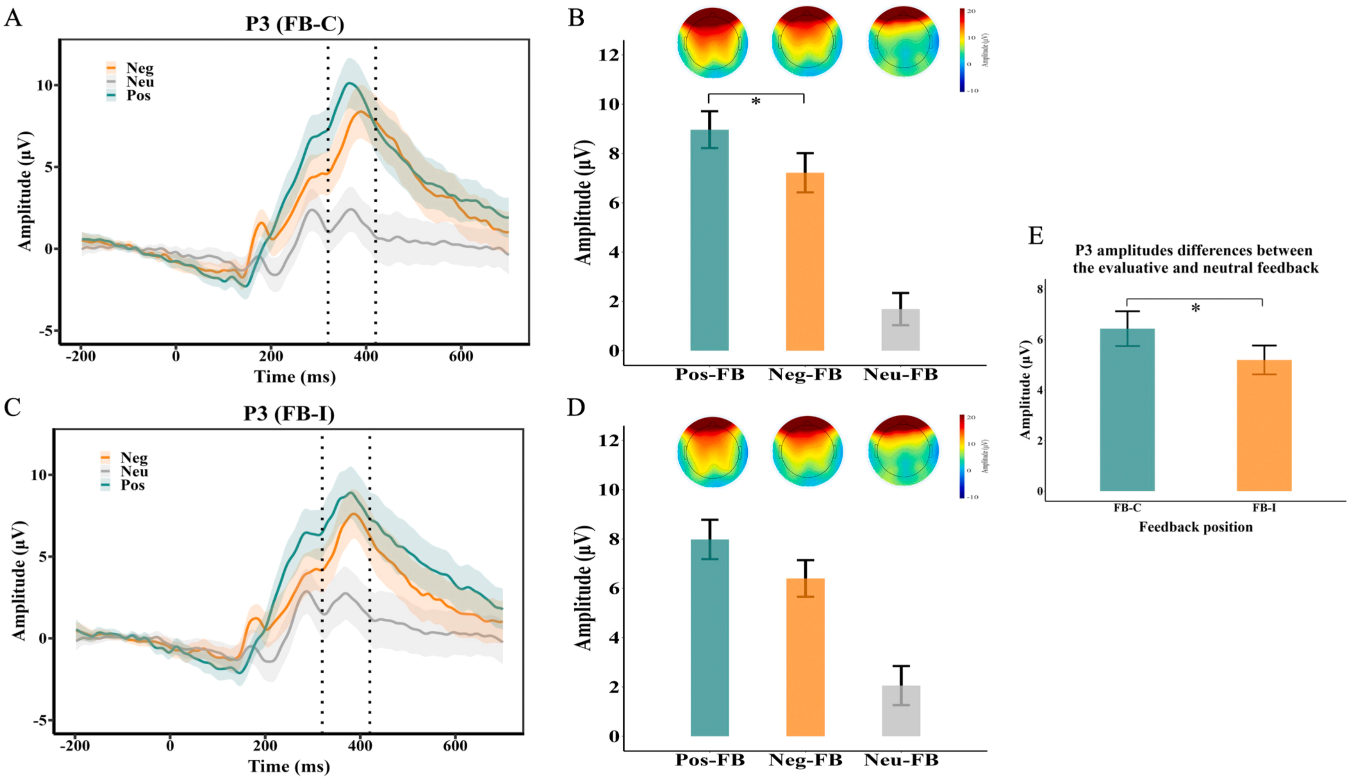

Fig. 4. Feedback processing ERP results. **A.** Grand average ERP waveforms from Pz for the FB-C conditions. **B.** Mean P3 amplitude separately for the negative, positive, and neutral feedback in the FB-C conditions. **C.** Grand average ERP waveforms from Pz for the FB-I conditions. **D.** Mean P3 amplitudes separately for the negative, positive, and neutral feedback in the FB-I conditions. **E.** P3 amplitude computed as a difference between the evaluative and the neutral feedback, which was larger for the FB-C than the FB-I conditions. “*”: $p < 0.05$.

significance, $Fs \leq 1.052$, $ps \geq .310$.

4. Discussion

In this EEG study, we analyzed several electrophysiological correlates of cognitive control in the time and time-frequency domains to assess if they could vary depending on the specific contingency created between conflict and performance feedback at the block level during a standard interference task. To this end, we administered the confound-minimized Stroop task to a large group of participants while 64-channel EEG was recorded, and using a block design, we reinforced either conflict (i.e., incongruent trials) or no-conflict (i.e., congruent trials). Based on previous behavioral results (Prével et al., 2021; Yang et al., 2022) as well as the DMC framework (Braver, 2012), we reasoned that whereas the former condition should decrease the congruency effect that relates to proactive control, the latter one should instead increase conflict adaptation, which is a proxy of reactive control. Consistent with this assumption and dominant theoretical model, we found at the behavioral level that the selective pairing of incongruent trials with the performance feedback decreased the congruency effect, while conflict adaptation improved when this pairing concerned congruent trials. Moreover and orthogonally to this main manipulation, the feedback had either high or low motivational value because it was either punishment-related or lacking this feature. However, it did not influence this flexibility. Importantly, these cognitive control changes found at the behavioral level were also reflected by the modulation of specific ERP components that were either stimulus (i.e., N450, P1) or feedback-locked (i.e., P3). Here after, we discuss the theoretical implications of these new results.

First, at the subjective level (i.e., PANAS and dislike feelings), participants reported higher levels of negative affect in the punishment compared to the no-punishment conditions. Moreover, negative affect increased the most when the performance feedback selectively reinforced incongruent trials (i.e., FB-I conditions), suggesting that participants did perceive the (evaluative) feedback differently depending on feedback position and punishment. More specifically, when associated with punishment, the feedback likely increased aversive motivation (Yee et al., 2022). Likewise, because conflict is aversive and triggers enhanced cognitive control (Dignath et al., 2020; Dreisbach & Fischer, 2015; Inzlicht et al., 2015), its systematic pairing with the performance feedback could also increase aversive motivation, especially in a context where this feedback has a high probability of being negative, as used here (see also Yang et al., 2022). More generally, these results accord with recent motivational accounts according to which cognitive control is grounded in negative affect (Inzlicht et al., 2015).

Second, at the behavioral level, we found that conflict adaptation improved (albeit slightly) when non-conflict was selectively paired with

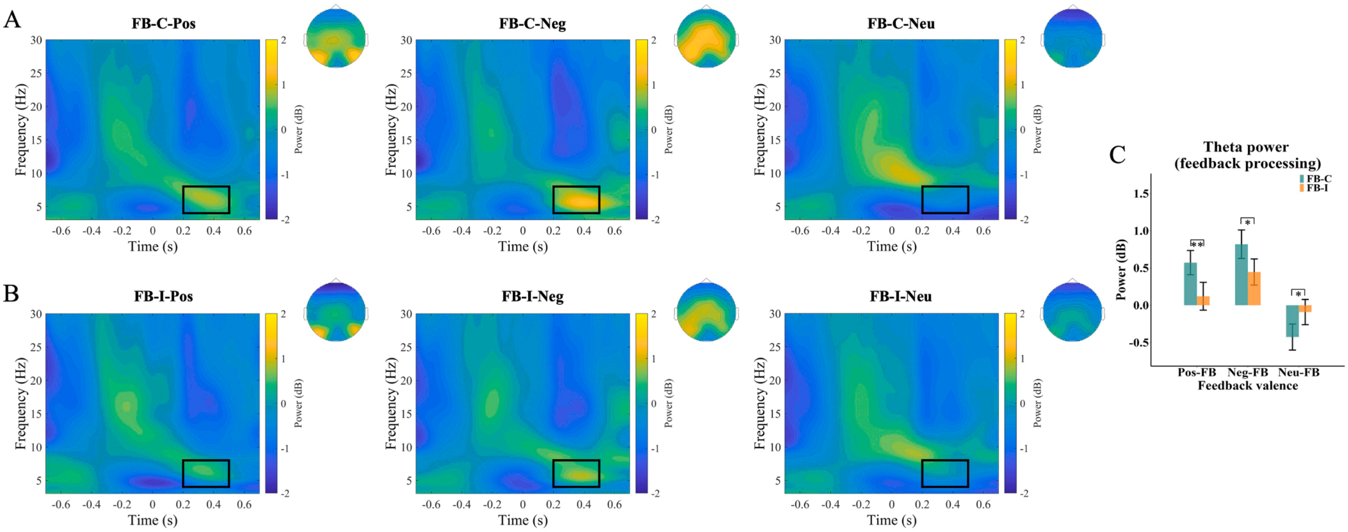

Fig. 5. Feedback processing MFT results. A. MFT (4–8 Hz) power changes from electrode Fz separately for the negative, positive, and neutral feedback in the FB-C conditions. B. Same for the FB-I conditions. The black rectangle superimposed indicates the area used for data analysis and scoring of MFT. C. Mean MFT power for the evaluative feedback was larger in the FB-C than the FB-I conditions, whereas it was smaller in the FB-C than the FB-I conditions for the neutral feedback. “**”: $p < 0.01$, “*”: $p < 0.05$.

the performance feedback (i.e., FB-C conditions), whereas a smaller congruency effect was observed when conflict was selectively paired with the performance feedback (i.e., FB-I conditions). This outcome is compatible with the DMC framework (Braver, 2012), suggesting that in this Stroop task and depending on this contingency, either reactive or proactive control was likely engaged. More specifically, in the FB-C conditions, reactive control, which is best captured by conflict adaptation, improved, while in the FB-I conditions, proactive control changed instead because the congruency effect was modulated. This finding is partially in line with several previous studies. More specifically, Zhang et al. (2022) and Prével et al., (2021, Experiment 3) found that the congruency effect increased when reward selectively followed congruent trials, whereas this effect (i.e., Simon effect) was reduced or even reversed when reward selectively followed incongruent trials. In comparison, Mittelstädt et al. (2023) observed that the modulation of the congruency effect by reward contingency occurred in the Simon and Eriksen flanker tasks, but not in the Stroop task. Hence, in these previous studies as well as the current one, the congruency effect was modulated by feedback contingency. However, Mittelstädt et al. (2023) reported no modulation of the congruency effect with the Stroop task while we found it here in this study. Tentatively, this discrepancy might be attributed to methodological or even motivational factors, including the use of reward in Mittelstädt et al. (2023) as opposed to aversive motivation in ours.

Hence, feedback position could modulate the expression of cognitive control at the behavioral level (Prével et al., 2021; Yang et al., 2022). In other words, when conflict trials were selectively paired with the performance feedback at the block level (with this information being explicitly conveyed to the participants by means of specific instructions), it could serve as a potent “cue” to inform them about conflict handling and resolution; this way fostering a form of preparatory control to some extent that was likely implemented with the goal to avoid the encounter of negative feedback (Causse et al., 2013; O’Doherty et al., 2001). In contrast, when congruent rather than incongruent trials were selectively paired with the performance feedback (i.e., FB-C), the default reactive control mode was activated, increasing in turn conflict adaptation, although to a modest degree (Duprez et al., 2020; Hayden & Platt, 2010). However, at odds with our previous study (Yang et al., 2022), this dissociation was not stronger for blocks where punishment was used at the feedback level compared to neutral blocks where it was not. Because punishment did produce an increase in negative affect at the subjective level (see PANAS and dislike feelings), as well as an increase of the P3 component at the EEG level, this lack of modulation of cognitive control by punishment cannot easily be attributed to a weak or inefficient elicitation of aversive motivation in the current study, we think. However, a notable methodological difference between this study and our previous one is that in the latter one, participants were not informed beforehand about the specific contingency created between the stimulus congruency and performance feedback at the block level. In the current study, this information was explicitly conveyed to them prior to each and every block, which presumably could influence cognitive control and possibly reduce the impact of aversive motivation on it because they would mostly monitor and use this contingency rather than the enhanced motivation value of the feedback in punishment blocks. Future studies are needed to explore this possibility further. In this context, it is noteworthy that in a recent study, we reported a modulation of cognitive control (i.e., the congruency effect) by punishment when meta-control was considered, i.e., the awareness of the contingency created between conflict and performance (Yang et al., 2023).

At the ERP level, we found larger N450 amplitudes for incongruent than congruent trials, replicating previous studies revealing that this component is sensitive to conflict processing when complex tasks, such as the Stroop task, are used (Larson et al., 2009). Importantly, we found that in the FB-I conditions, the N450 component showed comparable amplitudes for congruent and incongruent trials, as if the latter condition elicited less or even no conflict. This ERP result parallels the behavioral results showing that in this condition (FB-I), the congruency effect decreased. Moreover, a decreased N450 difference between congruent and incongruent trials has already been linked in the past to reduced interference in the Stroop task (Larson et al., 2009; West & Alain, 2000). Hence, when conflict was selectively reinforced by the performance feedback (i.e., FB-I), proactive control could be elicited whereby a more efficient processing of conflict could take place, in turn reducing the N450 component. In agreement with this assumption, we also found that in the FB-I conditions, a higher value was found for frontal alpha asymmetry than in the FB-C conditions (see also Schmid et al., 2015). Interestingly, no such amplitude modulation of the N450 component during conflict processing was observed in the FB-C conditions, for which conflict adaptation, but not the congruency effect, improved at the behavioral level. This dissociation is compatible with previous EEG studies that already reported that the N450 mostly captures within-trial conflict processing as opposed to cognitive control adjustments occurring across successive trials, as reflected by conflict adaptation (McKay et al., 2017; Larson et al., 2009). In agreement with this interpretation and the use of a proactive control mode in the FB-I conditions, we also found that the N450 component had overall a larger amplitude in them compared to the FB-C conditions, indirectly suggesting that the word stimulus probably led to enhanced cognitive control (irrespective of congruency) in the former condition. Moreover, when we considered the conflict SP for which less robust statistical results were found than the N450 (see Supplementary materials), it turned out to be numerically larger for incongruent than congruent trials in the FB-I conditions, selectively. In contrast, in the FB-C conditions where reactive control prevailed, the conflict SP did not capture conflict adaptation, despite its manifestation at the behavioral level (Larson et al., 2009, 2014; Shen et al., 2013). Hence, not only the N450 component, but also the conflict SP appears to be involved in proactive cognitive control, even though they might have dissociable roles in this process (Clayson et al., 2024; Larson et al., 2016).

Remarkably, our analysis of the P1 component, which arose earlier than the N450 after word onset and mostly captured extrastriate visual cortex activity in response to the (word) stimulus, was actually larger in the FB-I than the FB-C conditions; a result which is also compatible with the use of a proactive control mode in the former conditions. This result suggests that the Stroop stimulus was processed more strongly in the FB-I relative to the FB-C conditions at an early stage of sensory processing in the visual cortex, probably because more attention was allocated to it (Hillyard et al., 1998; Hopfinger & Mangun, 2001; Zhang et al., 2023). More specifically, we could assume that in the FB-I conditions, because of proactive control, a putative gain control process could operate, whereby attention could be directed to the goal-relevant dimension (i.e., the color of the Stroop stimulus) while downplaying or even suppressing the irrelevant one (i.e., the meaning of the word), thereby facilitating task performance (Appelbaum et al., 2012; Egner & Hirsch, 2005). Hence, sensory amplification, likely resulting from proactive control and a gain control mechanism, was observed in the FB-I conditions (Appelbaum et al., 2012). In turn, this sensory amplification could ease conflict processing at a later stage in the medial prefrontal cortex, as reflected by the N450 ERP component.

If the FB-I conditions led to proactive control, as we assume based on the behavioral results but also the N450 and P1 components, then feedback processing at the P3 level should also differ between the FB-I and FB-C conditions. Consistent with this conjecture, we found that in the FB-C conditions, the positive feedback (informing about an optimal level of performance) elicited a larger P3 component relative to the negative feedback (informing about a suboptimal one), while this difference was not observed in the FB-I conditions. Moreover, there was a larger P3 amplitude difference between the performance feedback (i.e., negative and positive feedback combined) and the neutral feedback in the FB-C than the FB-I conditions. In light of these results, it is plausible to assume that participants assigned a greater and differential motivational value to the performance feedback in the FB-C conditions, considering that the P3 has previously been linked to the attentional or motivational processing of relevant stimuli, including performance feedback (Balconi & Crivelli, 2010; Franken et al., 2011; Nieuwenhuis et al., 2005). Because this motivational effect was not found at the FRN level, our results indirectly confirm that these two successive feedback-locked ERP components likely capture different processes during performance monitoring and cognitive control (Yeung & Sanfey, 2004). Feedback contingency mostly altered the motivational significance of the feedback at the P3 level, rather than its (earlier) evaluation as either good or bad outcome at the FRN level. However, even though when controlling for the slight imbalance in the proportion of negative feedback between the FB-I and FB-C conditions did not alter these P3 results (see Supplementary materials), the interaction between Feedback valence and Feedback position became marginally significant only in this control analysis, thereby suggesting that caution is needed in the interpretation of this P3 effect as reflecting only the motviational significane of the feedback.

Combined together, these stimulus- and feedback-locked ERP results point to a likely double dissociation between the FB-C and FB-I conditions (see Table 3): in the FB-I conditions, the participants allocated more attention (P1) and engaged more intensively with the information provided at the stimulus than feedback level, which in turn could facilitate conflict processing, as reflected by the N450, as well as the conflict SP. This pattern could be consistent with the use of a proactive control mode. In comparison, in the FB-C conditions, the participants tended to rely more on feedback as opposed to stimulus processing, as mostly reflected by the P3 results. Because we also found improved conflict adaptation in these conditions, we could assume that this enhanced processing of the performance feedback might signal or promote the need to enhance cognitive control; an effect that would be reactive in nature. These results suggest that depending on the specific contingency created at the block level between feedback and performance, different cognitive control modes were likely activated to deal with conflict. Hence, they suggest that cognitive control is flexible and participants could tip the balance toward either stimulus or feedback processing depending on this contingency. More generally, these results are compatible with the notion that both proactive and reactive control are efficient strategies to deal with conflict, and depending on the specific contingency created between feedback and performance, participants can flexibly use them (Bejjani et al., 2020; Goschke, 2013; Mäki-Marttunen et al., 2019). However, even though the congruency effect and conflict adaptation effect could reflect proactive (sustained) and reactive (transient) cognitive control, respectively, this does not imply that the two effects are independent from each other. Rather than antagonist forces giving rise to cognitive control, they could be seen as complementing each other. In agreement with this assumption, we found a positive relationship (i.e., bivariate correlation) between the congruency effect and the conflict adaptation effect in the FB-C condition, where a larger conflict adaptation effect was associated with a larger congruency effect. Yet, in the FB-I condition, this relationship was not found, probably because the congruency effect was attenuated and hence unable to modulate conflict adaptation, considering that variations in conflict levels can modulate conflict adaptation (see Forster et al., 2011; Zhang et al., 2021).

However, given that proactive and reactive control can also be studied with other experimental paradigms where conflict processing is absent (such as the AX-CPT or DPX tasks; see Braver et al., 2009), it appears important in future EEG studies to assess whether similar ERP effects could be replicated with them or not. As a matter of fact, we cannot be hundred percent sure that the congruency effect and the conflict adaptation effect explored in this study are unambiguously related to proactive and reactive control, respectively. Yet, this might turn out to be challenging for the N450 ERP component (or conflict SP) because it is mostly triggered by conflict at the stimulus level. In comparison, it is probably more feasible for the P1, P3, as well as MFT and frontal alpha asymmetry, which can all also be elicited by (visual) stimuli devoid of conflict. Furthermore, in order to gain a mechanistic understanding of these cognitive control effects, it would be extremely valuable in future studies to use formal computational models of this ability (Botvinick et al., 2001; Shenhav et al., 2013; Verguts, 2017). Notwithstanding this caveat and limitations, and in agreement with our interpretation of a differential cognitive control mode used by the participants in the FB-C conditions (i.e., reactive control), we also found that MFT power for the performance feedback was larger in these conditions than the FB-I ones, likely reflecting the differential meaning or utility of this feedback to unlock behavioral changes in the former ones (Luft, 2014).

Interestingly, this intriguing dissociation found between reactive and proactive control at the ERP level was not reflected in MFT power (see also Mendl et al., 2024). At the stimulus level, MFT was larger for incongruent than congruent trials, whereas at the feedback level, it was larger for negative than positive or neutral feedback; yet irrespective of

Table 3
Summary of main EEG results found supporting a dissociation between the FB-I and FB-C conditions.

	Conflict processing			Feedback processing	
	P1	N450	Alpha asymmetry	P3	MFT
FB-I	Larger	Congruent = Incongruent	Larger		
FB-C		Incongruent > Congruent		Evaluative FB > Neutral FB	Evaluative FB > Neutral FB
Control mode	Proactive control	Proactive control	Proactive control	Reactive control	Reactive control

feedback position in these two cases. Thus, unlike these ERP components, MFT power did not capture these changes in cognitive control and hence this flexibility, suggesting that it could reflect a more general cognitive control effect (see Cavanagh & Frank, 2014). Although the N450 ERP component and MFT have both been linked to cognitive control engaged during conflict processing in the past (Hanslmayr et al., 2008; Nigbur et al., 2011, 2012), each of them could capture a different aspect of it (Cavanagh & Frank, 2014). Presumably, MFT could reflect the need or urge to enhance cognitive control upon the encounter of conflict or negative feedback (Chevalier et al., 2021; Nigbur et al., 2011), whereas the N450 (as well as the conflict SP to a lesser degree) could provide a more specific electrophysiological marker of the specific cognitive control strategy used by the participants to deal with conflict.

Another limitation is worth mentioning. The online and adaptive algorithm used to set the RT cutoff (see "Methods") was used to balance the proportion of negative and positive feedback in both conditions (FB-I and FB-C). Yet, despite its use, a slight asymmetry in the proportion of negative feedback was eventually found between these two conditions (i.e., FB-C: 53.8 % vs. FB-I: 68.7 %), which might complicate a straightforward between them at the EEG level. Hence, a slight asymmetry in local feedback processing between the FB-I and FB-C conditions (Osinsky et al., 2014), as opposed to reinforcement learning, might account for the feedback-locked effects found and reported in our study. Although we ran a control analysis where we matched trial number between these two conditions and found similar ERP results at the feedback level (see Supplementary materials), the experience of negative feedback by the participants was eventually larger in the FB-I than FB-C conditions and this control analysis could not mitigate this imbalance at the emotional level between conditions. Hence, this emotional effect, rather than reinforcement learning per se, might account for the observed ERP effect at the feedback level. However, we note that this imbalance was actually modest numerically and hence its impact (on the feedback-locked ERP data) must have been limited. Even though we cannot completely rule out its impact on the stimulus-locked ERP data either (i.e. P1 and N450 components), since we had the same proportion of congruent vs. incongruent trials in these two conditions alike, this alternative interpretation appears even less plausible than for the feedback-locked ERP data. This algorithm prevented the expression of obvious changes of RTs or accuracy across time, and was used to counter effects of fatigue and/or frustration (see Vocat et al., 2008). This was also confirmed by a control analysis where we assessed whether these differential cognitive control effects found at the behavioral level might change as a function of time on task (see Supplementary materials). Because the results of this control analysis failed to reveal clear improvements across time, an interpretation of our results in terms of reinforcement learning warrants caution, however. It might be that these behavioral and EEG effects were mostly driven by the instructions given to the participants, rather than reinforcement learning operating on a trial by trial basis.

In conclusion, our results show that cognitive control is flexible in the sense that two distinct control modes, namely reactive and proactive control (Braver, 2012), likely coexist and can each be recruited depending on the specific contingency created between performance feedback and conflict at the block level. When selectively reinforcing conflict, the congruency effect decreased. In comparison, when selectively reinforcing non-conflict, conflict adaptation benefited from this specific contingency. Accordingly, we can assume that the former condition fostered proactive control while the latter one induced reactive control. In agreement with this interpretation and theoretical model (Braver, 2012), we found that the former condition led to an amplitude modulation of the N450 component, but also a general increase of the P1 component early on following stimulus onset in the visual cortex. The latter condition instead mostly led to a change of feedback processing at the P3 level as if the performance feedback gained enhanced motivational significance in this condition. Moreover, frontal alpha asymmetry also changed depending on the contingency created between congruency and the performance feedback and was larger when incongruent trials were reinforced, suggesting the use of a proactive control mode in this condition. Hence, our new results show that proactive control, which reduced the congruency effect, influenced an early stage of sensory processing in the visual cortex (P1, likely by means of a gain control effect related to selective attention) as well as a later cognitive control component (N450), but it decreased the motivational processing of the performance feedback (P3). Conversely, reactive control did not influence the P1 or N450 ERP component, but it boosted feedback processing, which might be a pre-requisite to enable conflict adaptation across successive trials. These findings contribute to a growing understanding of cognitive control. Remarkably, distinct cognitive control modes can be set off in the same participants depending on the specific reinforcement created between conflict and performance. Moreover, because they lead to different electrophysiological manifestations, future EEG studies could harness them more directly to further explore the flexibility of cognitive control and eventually inform about its boundaries.

CRediT authorship contribution statement

Qian Yang: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Gilles Pourtois:** Writing – review & editing. **Jintao Xing:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization.

Ethics statement

This study was approved by the Ethical Committee of the Institute of Brain and Psychological Sciences at Sichuan Normal University and was performed in line with the 2013 Declaration of Helsinki.

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Declaration of Generative AI and AI-assisted technologies in the writing process

The authors did not use generative AI technologies for preparation of this work.

Data availability statement

The data and scripts used in this study are made publicly available using OSF (https://osf.io/swbqe/).

Declaration of Competing Interest

All authors declared no competing interests.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2025.109059.

Data availability

I have shared the link to my data and scripts in the manuscript.

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