

# Cognitive control is quickly adapted to actual task requirements despite misleading context cues—Evidence from the N2, CRN, and ERN

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## Abstract

Cognitive control is flexibly adapted to task requirements in healthy individuals. Medio-frontal negativities in the event-related potential of the electroencephalogram can serve as indicators of cognitive control. With increasing conflict frequency, stimulus-locked control, as indexed by the N2, is increased and response-locked control, as indexed by the correct-related negativity, is reduced. On the behavioral level, this shift is associated with improved conflict resolution as evident in reduced response times and error rates in incompatible trials and a reduced response time congruency effect. Cognitive control adaptation might be implemented through experience-based task sets specifying advantageous processing strategies. Here, we investigated whether the cognitive control task set will be sustained when coupled with a contextual cue, even when the initial task requirements are no longer present. A flanker task with two conflict frequency conditions (25% incompatible and 75% incompatible trials) was presented. In the training phase, the conflict frequency conditions were paired with a distinct context cue (i.e., background color). In the test phase, the previously associated cues were again presented, but conflict frequency was identical in both conditions (50% incompatible trials). Although typical cognitive control adaptation was observed in the training phase on the behavioral and event-related potentials level, this pattern was not sustained in the test phase. Thus, the present study provides further evidence that cognitive control is flexibly adapted to task requirements even in the presence of misleading cues.

## KEYWORDS

cognitive control, CRN, ERN, N2, proportion congruency effect, task set

## 1 | INTRODUCTION

Performance and conflict monitoring are central human abilities that are essential for adaptation to different environmental demands. They specifically come into play, when

the individual is confronted with situations triggering conflicting response tendencies. Besides behavioral measures, performance and conflict monitoring are reflected in several medio-frontal negativities observed in the event-related potentials (ERP) of the electroencephalogram (EEG). The

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N2 occurs about 200–350 ms after stimulus presentation and serves as a measure of conflict-related cognitive control (van Veen & Carter, 2002a). In response-conflict tasks, such as the flanker task, the N2 is larger when more executive control is needed in order to inhibit conflicting information (Bartholow et al., 2005; Grützmann et al., 2014). The correct-related negativity (CRN) occurs 0–100 ms following correct responses and is thought to index response monitoring (Endrass et al., 2012; Grützmann et al., 2014; Klawohn et al., 2014) and postresponse recruitment of cognitive control (Bartholow et al., 2005; Grützmann, Riesel, et al., 2014). The error-related negativity (ERN) occurs 0–100 ms after erroneous responses. It has a larger amplitude than the CRN and is thought to reflect error detection and processing (Falkenstein et al., 1990; Gehring et al., 1993). Thus, both the CRN and ERN reflect postresponse evaluation aiming to detect discrepancies between optimal and actual responses (Roger et al., 2010). In the case of suboptimal responding, such as errors, slow responses, use of improper response strategies, or even uncertainty about response correctness, cognitive control is recruited to reactively adapt the response mode on the next trial. The magnitude of the reactive control signal appears to be related to the severity of the suboptimal response (i.e., errors elicit a larger signal than slow responses or responses with a suboptimal strategy). All three medio-frontal ERP components are generated in the midcingulate cortex and adjacent areas (Debener et al., 2005; Grützmann et al., 2016; Van Veen & Carter, 2002b) indicating a common underlying neuronal system of cognitive control (Cavanagh et al., 2012), which can be activated at different time points during task processing. In line with this, the midcingulate cortex has been shown to be active in response to a wide array of unfavorable events ranging from negative performance feedback to physical pain and has thus been conceptualized as a universal detector of unfavorable events (Ridderinkhof et al., 2004).

Previous studies have shown that the monitoring processes are flexibly adapted to situational requirements in healthy individuals. In conflict tasks, a higher proportion of conflict stimuli results in improved conflict resolution as reflected in decreased response time and enhanced accuracy for incompatible trials (Bartholow et al., 2005; Corballis & Gratton, 2003; Grützmann et al., 2019; Grützmann, Riesel, et al., 2014; Jiang et al., 2013; Kalanthroff et al., 2014; Wendt et al., 2008; Wendt & Luna-Rodriguez, 2009). In-depth analysis of behavioral data by response time distributional analysis (van den Wildenberg et al., 2010) indicates that this proportion congruency effect is caused by an increase in interference inhibition (Grützmann, Riesel, et al., 2014). In line with this, behavioral congruency effects (i.e., the response time or error rate difference between incompatible and compatible trials) are reduced in conditions with a higher proportion of

conflict trials (Kuratomi & Yoshizaki, 2016). On the ERP level, this is accompanied by an increase in conflict-related cognitive control, as reflected in increased N2 amplitudes, and a decrease in response-related cognitive control as reflected in reduced CRN amplitudes (Bartholow et al., 2005; Grützmann, Riesel, et al., 2014). A similar pattern of increased stimulus-locked and decreased response-locked cognitive control has also been observed after a 3-week executive control training (Grützmann et al., 2021). Thus, the proactive implementation of stimulus-locked control (i.e., inhibition) may facilitate correct responding and thus reduce the need for trial-to-trial reactive strategy adjustment as reflected in the CRN. Flexible adaptations to task requirements are also observed for error monitoring. Punishing errors, that is, by monetary loss (Endrass et al., 2010; Hajcak et al., 2005) or application of aversive stimuli (Meyer & Gawłowska, 2017; Riesel et al., 2012, 2019), lead to increased ERN amplitudes. Similarly, increasing error significance through social evaluation also increases ERN amplitudes (Hajcak et al., 2005).

It has been argued that these changes are caused by tonic strategy adaptations (Ridderinkhof, 2002). More specifically, while performing a task, individuals develop a task set that guides behavior (Allport et al., 1994; Rogers & Monsell, 1995). The task set steers performance by specifying the way in which perception should be linked to action (Ridderinkhof, 2002). It is based, among other things, on the individual's intentions and expectations regarding the task and contains strategic properties, such as the degree of cautiousness or impulsivity that should be applied. For example, when errors are being punished, participants will most likely increase the cautiousness of their response (i.e., respond more slowly) and upregulate performance monitoring (Meyer & Gawłowska, 2017; Riesel, Kathmann, Wullhorst, et al., 2019; Riesel et al., 2012). In the same line of thought, when conflict frequency is high, the most successful and economic strategy may be to inhibit the irrelevant, potentially conflict-eliciting information continuously by recruiting proactive cognitive control (Desender & Van den Bussche, 2012). Previous research suggests that this is achieved by adapting visual selectivity (Kuratomi & Yoshizaki, 2016; Wendt et al., 2014) to focus specifically on the target stimulus. This adaptation comes at the cost of increasing response times to compatible trials (as nonconflict information is unnecessarily inhibited) but is behaviorally advantageous for incompatible trials. Thus, task requirements should be continuously monitored and task sets flexibly adapted.

In line with this, Kuratomi and Yoshizaki (2016) recently reported evidence for fast and highly flexible adaptation of cognitive control in the flanker task. They investigated whether adaptation to conflict frequency shows intermediate stability in healthy individuals. Specifically, they presented different conflict frequency conditions (83%, 75%, 50%,

25%, and 17% incompatible trials) in a training phase and investigated how long the behavioral adaptation would persist in a subsequent test phase with 50% incompatible trials. They found no evidence for temporal stability of the behavioral adaptation, that is, behavioral measures were identical across all groups regardless of which executive demand condition was presented in the training phase. In a second follow-up study, they additionally addressed the question of whether this “reset” of the task set only occurs when the different executive demand conditions are perceptibly divided for the participant by presenting them in two different blocks with a short break in between. To this end, they investigated behavioral adaptation to different executive demand conditions within one continuous block of trials. Again, behavioral data showed fast and adequate adaptation.

The aim of the present study was to investigate whether the task set containing strategic adaptation to conflict frequency will be sustained when coupled with a contextual cue. Specifically, we aimed to investigate whether the previously formed task set would still guide behavior when the original conflict frequency conditions were no longer active, but associated context cues were still presented. Behavioral studies have shown that the conflict frequency-related attentional adjustments can be associated with cue features such as stimulus location, color, or shape (Crump et al., 2006, 2008; Crump & Milliken, 2009; Vietze & Wendt, 2009; Wendt et al., 2008). However, to our knowledge, it has not been explored whether this effect extends to the underlying medio-frontal negativities. Hence, we coupled different levels of conflict frequency in a flanker task (25% incompatible trials vs. 75% incompatible trials) with task-irrelevant context stimuli (yellow vs. blue background) in a training phase. In the following test phase, the background color was still varied blockwise, but conflict frequency was 50% in both color conditions. In a previous study, Riesel and colleagues (2012) used a similar design to investigate learning effects on the ERN amplitude. In the acquisition phase, the color of the flanker stimuli was varied in a blockwise fashion. Errors in one color condition were followed by punishment (i.e., an aversive sound), which lead to increased ERN amplitudes. In the test phase, stimuli were still presented in different colors, but the punishment was no longer applied. Importantly, participants still showed increased ERN amplitudes in the formally punished color condition, indicating that participants formed a stable task set that was associated with context cues and still applied when learning conditions were no longer present. In the present study, we investigated whether conflict frequency adaptations would behave similarly. First of all, we expected to replicate previous results of tonic conflict adaptation on the behavioral and ERP level (i.e., Bartholow et al., 2005; Grutzmann et al., 2019; Grützmann, Riesel, et al., 2014). Specifically,

a higher conflict frequency should be associated with increased stimulus-locked cognitive control as indexed by the following effects for incompatible trials in the training phase: (a) reduced response times, (b) increased accuracy, (c) increased N2 amplitudes, and (d) decreased CRN amplitudes. As ERN magnitude has been shown to be negatively related to error rates (Gehring et al., 1993; Riesel et al., 2019), we expected larger ERN amplitudes in the 75% incompatible condition. Furthermore, we investigated whether the task sets for low versus high conflict frequency would be transferred to the test phase. Specifically, if the task set was guided by context cues, behavioral and ERP differences between the color conditions should persist in the test phase, even though both conditions contain 50% incompatible trials. In order to further explore their temporal stability, cue effects were compared between the beginning and the end of the test phase. We expected updating of the task sets over time. Thus, the cue effects should be stronger at the beginning of the test phase.

## 2 | METHOD

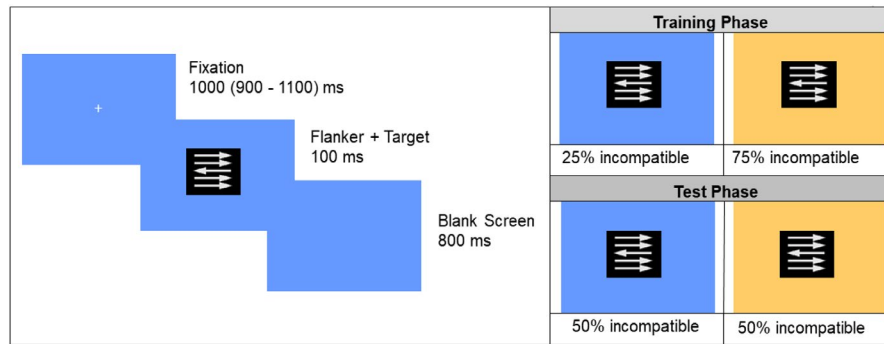
### 2.1 | Participants

Participants were 36 adults<sup>1</sup> (25 women) with a mean age of 26 years (*SD*: 6.02, range 18–46 years) who signed informed consent. They were students at the Humboldt-Universität zu Berlin and received course credit for their participation. All participants had a normal or corrected-to-normal vision and reported no neurologic diseases or history of head trauma. Data of six participants were discarded because of technical malfunctions, resulting in a sample of 30 participants (19 women, mean age 26 years, *SD*: 5.22, range: 18–38 years).

### 2.2 | Stimuli and procedures

A modified version of the flanker interference task (Eriksen & Eriksen, 1974; Kopp et al., 1996, see Figure 1) was presented using Presentation (Neurobehavioral Systems, San Francisco, CA). Stimuli were displayed in white against a black background on a 19-inch computer monitor (refresh rate 100 Hz). At a viewing distance of 70 cm, the set of arrows was approximately 1.2° of visual angle wide and 1.2° of visual angle tall. Each trial was either compatible (target and flanker arrows pointed in the same direction)

<sup>1</sup>A priori power analyses, described in detail in the Supporting Information, indicated a required sample size of  $n > 18$  for behavioral analysis and  $n > 33$  for CRN analysis in order to detect the expected interactions of compatibility and cue condition with a power of  $> 80$ .



**FIGURE 1** Experimental design of the flanker task: Flanker stimuli were presented superimposed on a yellow or blue background. Participants were instructed to respond fast and accurately with their left or right index finger to the target arrow. The experiment consisted of two phases with two blocks each. The training phase comprised two blocks with different background colors containing 25% (frequent compatible, FC condition) and 75% incompatible trials (frequent incompatible, FI condition), respectively. The test phase consisted of two blocks with the same background colors as in the training phase, but conflict frequency was 50% for both blocks

or incompatible (target and flanker arrows pointed in opposite directions). Participants were instructed to respond as quickly and accurately as possible to the direction of the central target arrow by pressing the corresponding key. The experiment consisted of two phases, each comprising two blocks. In the training phase, two blocks with different conflict frequencies were presented. One block contained 25% incompatible trials (frequent compatible, FC), whereas the other block contained 75% incompatible trials (frequent incompatible, FI). Conflict frequency conditions were paired with a distinct context cue. Specifically, flanker stimuli were displayed on a colored background, which was either yellow or blue. Assignment of colors to conflict frequency conditions was balanced across participants. In the following test phase, two blocks were presented in which stimuli were again displayed on a yellow or blue background. However, the frequency of incompatible trials was 50% in both color conditions. The order of cue conditions was varied pseudo-randomly across participants but kept parallel between the training phase and test phase for each individual. Target direction (left vs. right) was balanced within each condition and was varied pseudo-randomly across trials. Each block comprised 400 trials, adding up to a total experiment duration of about 60 min (including breaks).

### 2.3 | Electrophysiologic recording and data analysis

EEG and electrooculographic (EOG) activities were recorded continuously with 64 Ag–AgCl electrodes including Cz as recording reference. Electrodes were mounted with an EasyCap electrode system (Falk Minow Services, Munich, Germany) based on an equidistant electrode position system. Additional electrodes were placed on five

external locations: IO1, IO2, Nz, neck, and cheek. The electrode on the cheek served as ground. Electrode impedances were kept below 5 k $\Omega$ . The EEG was recorded with a sampling rate of 1000 Hz and a band-pass filter of 0.01–250 Hz.

EEG data were processed with the Brain Vision Analyzer 2 (Brain Products, Gilching, Germany). Eye-movement artifacts were corrected using an automatic ocular correction independent component analysis. Continuous EEG signals were filtered with a high-pass filter of 0.1 Hz and a low-pass filter of 30 Hz and rereferenced to average reference. For N2 analysis, stimulus-locked epochs with a duration of 800 ms including 200 ms prestimulus interval were extracted. For CRN analysis, response-locked epochs with a duration of 600 ms including 200 ms prereponse interval were extracted. The interval from –200 to 0 ms prior to the stimulus or response, respectively, served as a baseline. Epochs containing artifacts exceeding  $\pm 200 \mu\text{V}$  in amplitude, voltage steps of more than 40  $\mu\text{V}$  between consecutive data points, or a minimum overall activity below 0.5  $\mu\text{V}$  were excluded from further analysis. Trials with response times exceeding 800 ms were also excluded. Averages were computed separately for each participant, for each phase (training phase and test phase), for each cue condition (FC and FI), and for compatible and incompatible trials. N2 averages included only correct trials. As only very few errors are committed in compatible trials, the ERN was only analyzed in incompatible trials. The N2 was quantified as mean amplitude in the time window 200–350 ms following the stimulus. The CRN and ERN were quantified as mean amplitude in the time window from 0 to 100 ms following correct responses. All components were calculated at Fz, FCz, and Cz.

Statistical analyses were conducted with SPSS (Version 23.0, Chicago, IL, USA). Repeated measurement analyses of variance (ANOVA) were used for analyses of



performance and ERP measures. Correct response times were analyzed using a repeated-measures ANOVA including the factors phase (training phase and test phase), cue conditions (FC and FI), and compatibility (compatible and incompatible). Absolute error rates across cue conditions are confounded with different amounts of incompatible trials. Therefore, relative error rates (percentage of errors in all incompatible trials in each cue condition) were computed. Only very few errors were committed in compatible trials; these were excluded from analyses. Error rates and error response times were analyzed using repeated-measures ANOVAs including the factors phase (training phase and test phase) and cue condition (FC and FI). N2 and CRN amplitudes were analyzed by a repeated-measures ANOVA comprising the factors electrode (Fz, FCz, and Cz), phase (training phase and test phase), cue condition (FC and FI), and compatibility (compatible and incompatible). ERN amplitudes were analyzed by a repeated-measures ANOVA, comprising the factors electrode (Fz, FCz, and Cz), phase (training phase and test phase), and cue condition (FC and FI). Two participants with fewer than five artifact-free error trials (Olvet & Hajcak, 2009) were excluded from the ERN analysis, resulting in an analysis sample of  $n = 28$ .

For the N2 and CRN, a follow-up analysis was conducted to explore the temporal stability of the cue effects. Each experimental condition was divided into five blocks of 80 trials. If gradual extinction occurs, cue effects should be more pronounced in the first block than in the last block of each condition in the test phase. In order to control for unspecific time-on-task effects on attention and response time, the congruency effect (incompatible trials–compatible trials) was used as the outcome variable. These follow-up analyses were computed for behavioral and EEG data. For EEG data, this analysis was conducted at the electrode at which the effect of cue condition was maximal in the main analysis. To assess the influence of blocks on cue effects, the ANOVAs described before were repeated with the additional factor

block (first block and last block). Due to an insufficient number of erroneous responses in the respective blocks, this analysis was not conducted for the ERN.

For all significant main effects or interactions, post-hoc comparisons were conducted using paired-sample  $t$  tests.  $T$  values,  $p$  values, effect sizes (Cohen's  $d$ ), and confidence intervals of effect sizes are reported for post-hoc comparisons.

## 3 | RESULTS

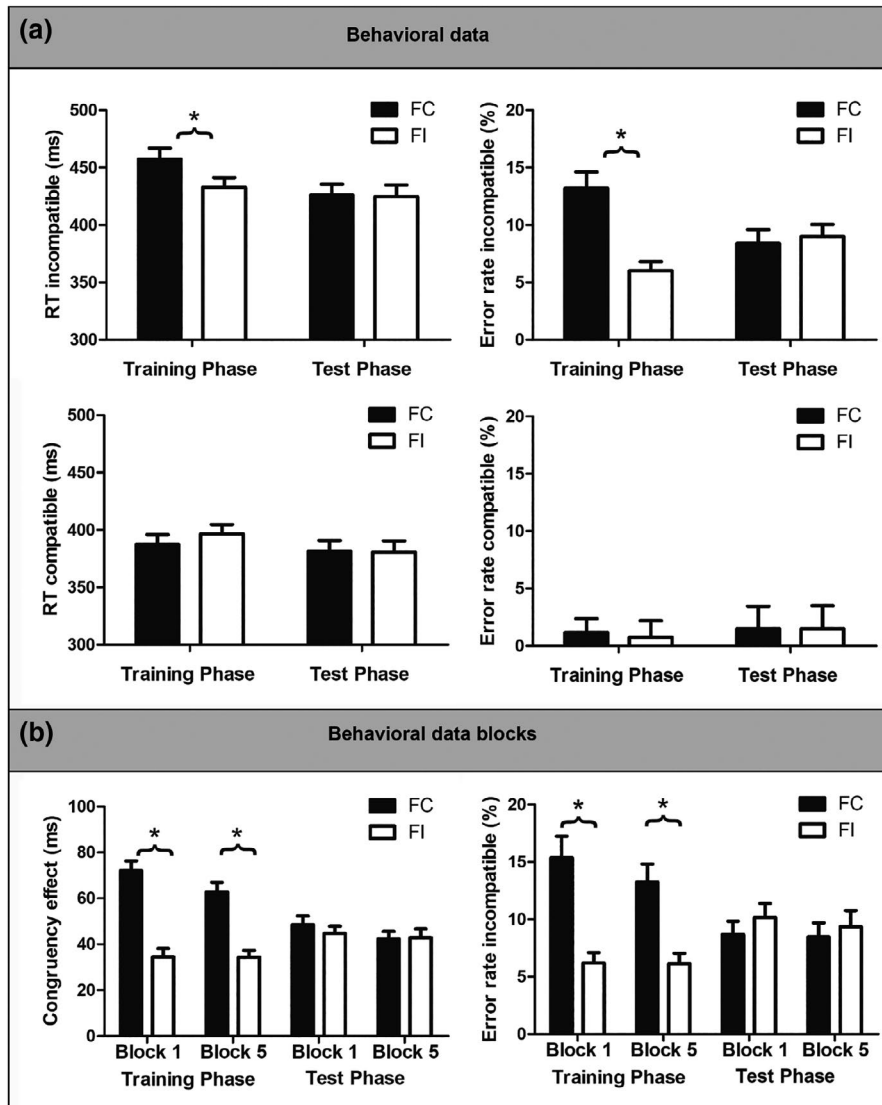
### 3.1 | Behavioral results

Response times and error rates are presented in Table 1 and Figure 2a. The  $2 \times 2 \times 2$  ANOVA (phase, cue condition, and compatibility) on correct response times yielded a significant main effect of compatibility,  $F(1,29) = 380.84$ ,  $p < .001$ ,  $\eta_p^2 = 0.93$ , indicating faster responses in compatible trials. A significant interaction of compatibility and cue condition was detected,  $F(1,29) = 91.62$ ,  $p < .001$ ,  $\eta_p^2 = 0.76$ , indicating that response times for incompatible trials were faster in the FI than in the FC condition,  $t(29) = -3.27$ ,  $p = .003$ ,  $d = 0.61$ , 95% CI [0.09, 1.12], whereas the modulation did not reach significance for compatible trials,  $t(29) = 1.33$ ,  $p = .194$ . This modulation of response times resulted in a reduced congruency effect in the FI condition compared with the FC condition,  $t(29) = 10.66$ ,  $p < .001$ . Furthermore, response times were significantly shorter in the test phase than in the training phase as reflected in a significant main effect of phase,  $F(1,29) = 13.19$ ,  $p = .001$ ,  $\eta_p^2 = 0.31$ . Additionally, significant interactions of phase and compatibility,  $F(1,29) = 38.41$ ,  $p < .001$ ,  $\eta_p^2 = 0.57$ , and phase, compatibility, and cue condition,  $F(1,29) = 83.03$ ,  $p < .001$ ,  $\eta_p^2 = 0.74$ , were detected. Follow-up tests showed that the effect of cue condition in

**TABLE 1** Error rates in incompatible trials and response times for erroneous and correct reactions in compatible and incompatible flanker trials in the training and test phase in the FC and FI conditions. Error rates are presented in % and response times are presented in ms

	Training phase				Test phase			
	FC		FI		FC		FI	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Error rate incom	15.81	16.35	8.95	16.81	11.20	16.78	11.60	15.57
Error rate com	1.17	1.21	0.75	1.44	1.50	1.95	1.50	2.00
Error RT incom	356.31	27.69	343.34	26.62	347.74	33.52	348.84	35.06
Correct RT incom	452.55	57.99	429.08	49.50	422.18	55.55	420.72	58.41
Correct RT com	386.79	46.11	395.95	44.03	380.82	50.99	380.08	52.98

Abbreviations: com, compatible; FC, frequent compatible; FI, frequent incompatible; incom, incompatible.



**FIGURE 2** (a) Response time (ms) and error rate (%) in incompatible and compatible trials in the FC and FI conditions in the training phase and test phase. Bars represent standard errors. (b) Response time congruency effect (incompatible–compatible trials, in ms) and error rate (%) in the first and last block of the FC and FI conditions in the training phase and test phase. Bars represent standard errors. FC, frequent compatible; FI, frequent incompatible. \* represent values significant at  $p = .050$

incompatible trials was present in the training phase,  $t(29) = -3.88, p = .001, d = 0.77, 95\% \text{ CI } [0.25, 1.30]$ , but absent in the test phase,  $t(29) = -0.34, p = .737$ . Correct response time in compatible trials tended to be slower in the FI than in the FC condition in the training phase,  $t(29) = 1.79, p = .085$ , but this effect was not observed in the test phase,  $t(29) = -0.29, p = .773$ . Accordingly, the congruency effect did not differ between the FI and FC condition in the test phase,  $t(29) = 0.22, p = .827$ .

The  $2 \times 2$  ANOVA (phase and cue condition) on error response times in incompatible trials yielded a significant interaction of phase and cue condition,  $F(1,29) = 4.38, p = .045, \eta_p^2 = 0.12$ , indicating that error response times

were significantly longer in the FC than in the FI condition in the training phase,  $t(29) = -2.15, p = .040, d = 0.41, 95\% \text{ CI } [-0.10, 0.92]$ , whereas no modulation was observed in the test phase,  $t(29) = 0.31, p = .761$ .

The  $2 \times 2$  ANOVA (phase and cue condition) on error rates yielded a significant main effect of cue condition,  $F(1,29) = 22.01, p < .001, \eta_p^2 = 0.43$ , that was further specified by its interaction with phase,  $F(1,29) = 42.13, p < .001, \eta_p^2 = 0.59$ . Error rates were significantly lower in the FI than in the FC condition in the training phase,  $t(29) = -6.55, p < .001, d = 1.95, 95\% \text{ CI } [1.34, 2.57]$ , whereas no difference was observed in the test phase,  $t(29) = 0.83, p = .415$ .

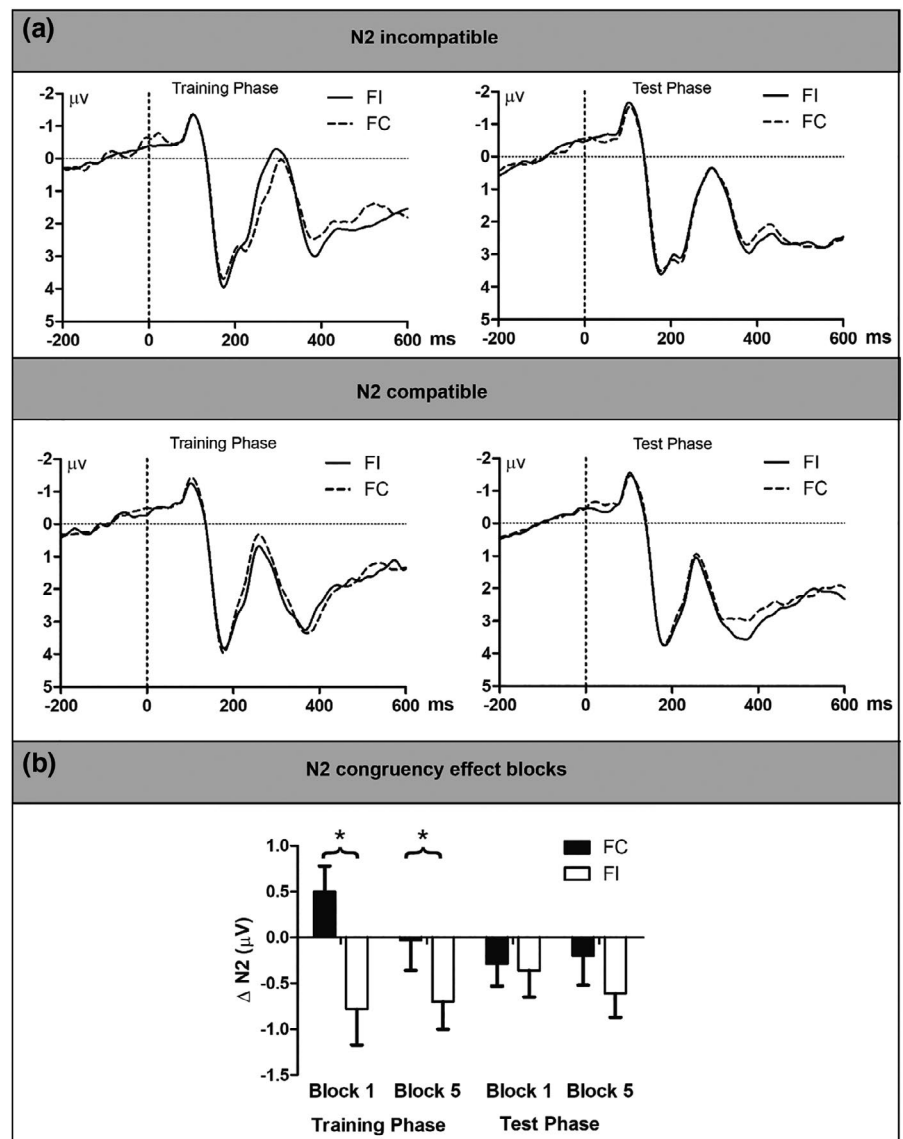
### 3.1.1 | Block analysis of behavioral data

Figure 2b illustrates the RT congruency effect and error rates in the first and the last block of each experimental phase.

The ANOVA on the RT congruency effect did not yield a significant main effect of or interactions with the factor block. Accordingly, the interaction of phase, cue condition, and block was not significant,  $F(1,29) = 0.46$ ,  $p = .502$ ,  $\eta_p^2 = 0.02$ . The ANOVA on error rates did not yield a significant main effect of or interactions with the factor block. Accordingly, the interaction of phase, cue condition, and block was not significant,  $F(1,29) = 1.07$ ,  $p = .310$ ,  $\eta_p^2 = 0.04$ . Thus, none of the behavioral measures significantly differed between the first and the last block of each condition.

### 3.2 | N2 results

ERPs are depicted in Figure 3a and amplitude values are presented in Table 2. The  $3 \times 2 \times 2 \times 2$  ANOVA (electrode, phase, cue condition, and compatibility) on N2 amplitudes yielded a significant main effect of electrode,  $F(2,58) = 12.33$ ,  $p < .001$ ,  $\eta_p^2 = 0.30$ , indicating that N2 amplitudes were largest at electrode Fz, of medium amplitude at electrode FCz and smallest at Cz (all  $p < .007$ ). A significant main effect of compatibility was observed,  $F(1,29) = 8.23$ ,  $p = .008$ ,  $\eta_p^2 = 0.22$ , indicating that N2 was larger for incompatible trials. A significant interaction of compatibility and electrode,  $F(2,58) = 12.92$ ,  $p < .001$ ,  $\eta_p^2 = 0.31$ , indicated that this effect was larger at electrode FCz ( $p = .005$ ) and Cz ( $p = .001$ ) than at electrode Fz ( $p = .188$ ).



**FIGURE 3** (a) Grand averages of the N2 at electrode Fz (μV) in incompatible and compatible trials in the FI and FC conditions in the training phase and test phase. (b) N2 amplitude congruency effect (incompatible–compatible trials, in μV) in the first and last block of the FC and FI conditions in the training phase and test phase. Bars represent standard errors. FC, frequent compatible; FI, frequent incompatible. \* represent values significant at  $p = .050$

**TABLE 2** Amplitude ( $\mu\text{V}$ ) of the N2 and the CRN at electrode Fz, FCz, and Cz in incompatible and compatible trials in the FC and FI condition in the training and test phases

	Training phase				Test phase			
	FC		FI		FC		FI	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Fz								
N2 incom	1.27	2.02	0.80	1.91	1.16	2.06	1.24	2.11
N2 com	0.97	2.01	1.47	1.86	1.39	2.10	1.57	2.02
CRN incom	-0.96	2.31	-0.29	2.16	-0.01	2.01	0.10	2.07
CRN com	-0.60	2.11	-1.09	2.20	-0.18	1.95	-0.20	1.97
ERN incom	-3.48	2.74	-3.84	2.45	-3.28	2.48	-3.35	2.37
FCz								
N2 incom	1.41	2.34	0.97	2.10	1.60	2.42	1.57	2.50
N2 com	1.61	2.26	1.92	1.92	2.21	2.45	2.41	2.50
CRN incom	-0.08	2.43	0.49	2.29	0.64	2.38	0.94	2.07
CRN com	0.47	2.54	-0.09	2.29	0.63	2.37	0.94	2.40
ERN incom	-4.74	3.83	-5.40	3.61	-4.46	3.32	-4.14	3.86
Cz								
N2 incom	2.06	2.38	1.61	2.06	2.31	2.43	2.25	2.59
N2 com	2.45	2.26	2.47	2.02	3.10	2.64	3.07	2.66
CRN incom	1.02	2.41	1.13	2.49	1.65	2.36	1.75	2.47
CRN com	1.66	2.71	1.12	2.54	1.96	2.89	1.92	2.60
ERN income	-3.97	4.00	-4.66	3.49	-2.94	3.31	-2.68	3.94

Abbreviations: com, compatible; FC, frequent compatible; FI, frequent incompatible; incom, incompatible.

A significant interaction of compatibility and cue condition was observed,  $F(1,29) = 14.18$ ,  $p = .001$ ,  $\eta_p^2 = 0.33$ . The N2 in incompatible trials was larger in the FI condition than in the FC condition,  $t(29) = 2.18$ ,  $p = .037$ ,  $d = -0.40$ , 95% CI [-0.91, 0.11]. The N2 in compatible trials was numerically larger in the FC than in the FI condition, but this modulation did not reach statistical significance,  $t(29) = -1.48$ ,  $p = .149$ . This effect was further specified by its interaction with electrode,  $F(2,58) = 5.10$ ,  $p = .009$ ,  $\eta_p^2 = 0.15$ , indicating that the modulation was stronger at electrode Fz ( $p = .005$ ) and FCz ( $p = .056$ ) than at electrode Cz ( $p = .922$ ).

Furthermore, a significant main effect of phase,  $F(1,29) = 8.23$ ,  $p = .008$ ,  $\eta_p^2 = 0.22$ , a significant interaction of electrode and phase,  $F(2,58) = 3.99$ ,  $p = .048$ ,  $\eta_p^2 = 0.12$ , a significant three-way interaction of phase, compatibility, and cue condition,  $F(1,29) = 10.33$ ,  $p = .003$ ,  $\eta_p^2 = 0.26$ , and a significant four-way interaction of electrode, phase, compatibility, and cue condition,  $F(2,58) = 4.63$ ,  $p = .021$ ,  $\eta_p^2 = 0.14$ , were observed. Taken together, these effects indicate that the N2 in incompatible trials was significantly larger in the FI than in the FC condition in the training phase,  $t(29) =$

$2.45$ ,  $p = .021$ ,  $d = -0.43$ , 95% CI [-0.94, 0.08], whereas no difference was observed in the test phase,  $t(29) = 0.03$ ,  $p = .974$ . The interaction with electrode further indicated that the effect of cue condition in the training phase was strongest at electrode Fz, where amplitudes were modulated for both compatibility conditions, but in opposite directions. The N2 in incompatible trials was larger in the FI condition,  $t(29) = -2.76$ ,  $p = .010$ ,  $d = 0.52$ , 95% CI [0.01, 1.03], whereas the N2 in compatible trials was larger in the FC condition,  $t(29) = 2.31$ ,  $p = .028$ ,  $d = -0.44$ , 95% CI [-0.95, 0.07].

### 3.2.1 | Block analysis of N2 amplitudes

Figure 3b illustrates the N2 amplitude congruency effect in the first and last block of each experimental phase. The ANOVA did not yield a significant main effect of or interactions with the factor block. Accordingly, the interaction of phase, cue condition, and block was not significant,  $F(1,29) = 1.76$ ,  $p = .195$ ,  $\eta_p^2 = 0.06$ . Thus, the N2 did not significantly differ between the first and the last block of each condition.



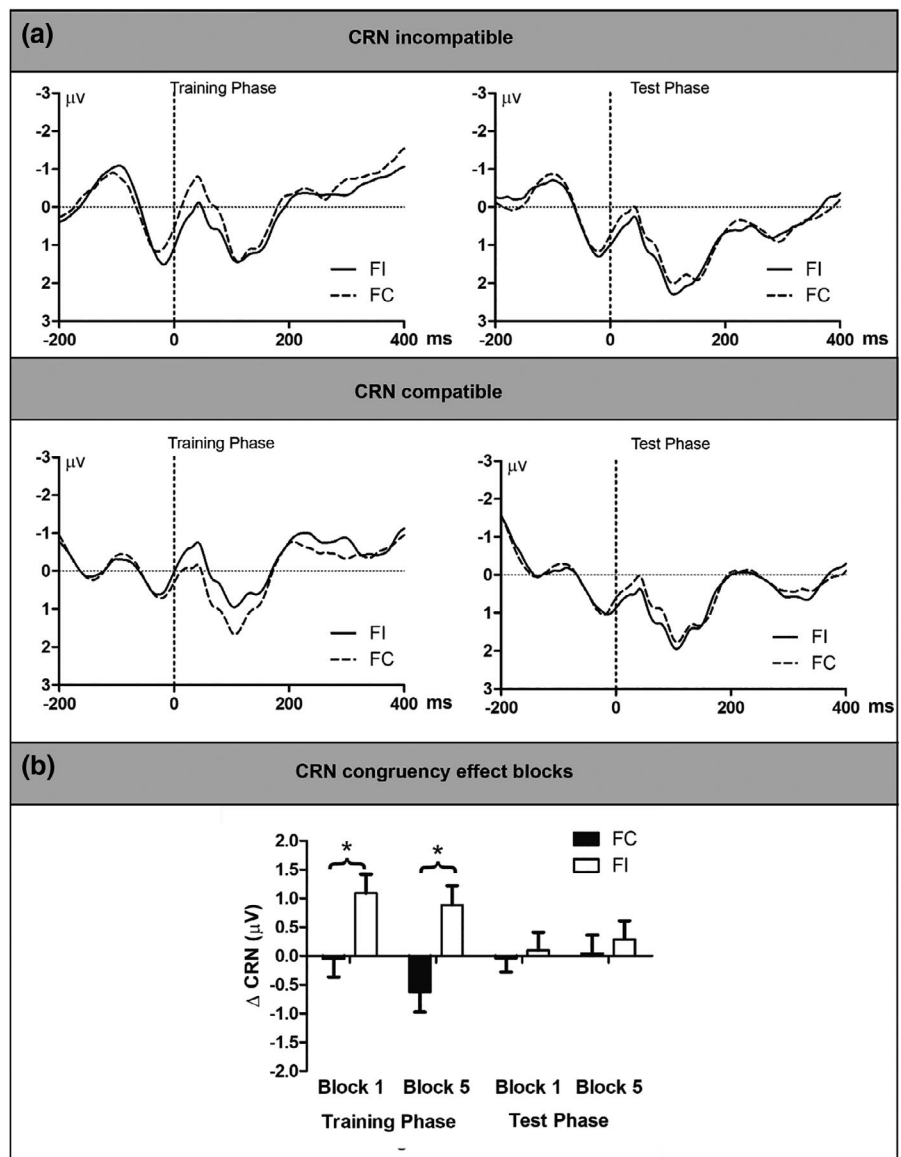
### 3.3 | CRN results

ERPs are depicted in Figure 4a and amplitude values are presented in Table 2. The  $3 \times 2 \times 2 \times 2$  ANOVA (electrode, phase, cue condition, and compatibility) on CRN amplitudes yielded a significant main effect of electrode,  $F(2,58) = 26.11$ ,  $p < .001$ ,  $\eta_p^2 = 0.47$ , indicating that CRN amplitudes were largest at electrode Fz, medium at FCz, and smallest at Cz (all  $p < .001$ ).

A significant interaction of compatibility and cue condition was detected,  $F(1,29) = 23.17$ ,  $p < .001$ ,  $\eta_p^2 = 0.44$ , indicating that the CRN in incompatible trials was significantly larger in the FC than in the FI condition,  $t(29) = 2.18$ ,  $p = .037$ ,  $d = -0.40$ , 95% CI  $[-0.91, 0.11]$ . The CRN in compatible trials was numerically larger in the FI than in the FC condition, but this did not reach statistical significance,  $t(29) = -1.48$ ,  $p = .149$ . The additional interaction of electrode and compatibility,  $F(2,58) = 12.78$ ,  $p$

$< .001$ ,  $\eta_p^2 = 0.31$ , and of electrode, compatibility and cue condition,  $F(2,58) = 4.61$ ,  $p = .014$ ,  $\eta_p^2 = 0.13$ , indicated that the effect of cue condition on CRN in incompatible trials was larger at electrode Fz ( $p = .002$ ) and FCz ( $p = .014$ ) than at electrode Cz ( $p = .512$ ).

Furthermore, a significant main effect of phase was observed,  $F(1,29) = 13.46$ ,  $p = .001$ ,  $\eta_p^2 = 0.32$ , indicating smaller CRN amplitudes in the test phase than in the training phase. Additionally, a three-way interaction of phase, compatibility, and cue condition,  $F(1,29) = 17.43$ ,  $p < .001$ ,  $\eta_p^2 = 0.38$ , and a four-way interaction of electrode, phase, compatibility, and cue condition were observed,  $F(2,58) = 5.43$ ,  $p = .016$ ,  $\eta_p^2 = 0.16$ . These effects indicate, that in the training phase, the CRN in incompatible trials was significantly larger in the FC than in the FI condition,  $t(29) = 2.47$ ,  $p = .020$ ,  $d = -0.48$ , 95% CI  $[-0.99, 0.04]$ , whereas no effect of cue condition were observed in the



**FIGURE 4** (a) Grand averages of the CRN at electrode Fz (µV) in incompatible and compatible trials in the FI and FC conditions in the training phase and test phase. (b) CRN amplitude congruency effect (incompatible-compatible trials, in µV) in the first and last block of the FC and FI conditions in the training phase and test phase. Bars represent standard errors. FC, frequent compatible; FI, frequent incompatible. \* represent values significant at  $p = .050$

test phase,  $t(29) = 1.05$ ,  $p = .304$ . The interaction with electrode showed that this pattern was present at electrode Fz ( $p = .001$ ) and FCz ( $p = .008$ ) but absent at electrode Cz ( $p = .691$ ).

### 3.3.1 | Block analysis of CRN amplitudes

Figure 4b illustrates the CRN amplitude congruency effect in the first and last block of each experimental phase. The ANOVA did not yield a significant main effect of or interactions with the factor block. Accordingly, the interaction of phase, cue condition, and block was not significant,  $F(1,29) = 0.14$ ,  $p = .711$ ,  $\eta_p^2 = 0.01$ . Thus, the CRN did not significantly differ between the first and last block of each condition.

### 3.4 | ERN results

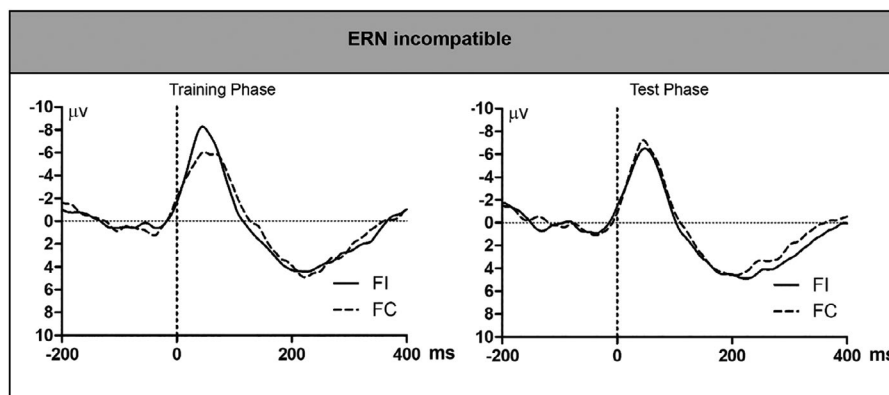
ERPs are depicted in Figure 5 and amplitude values are presented in Table 2. The  $3 \times 2 \times 2$  ANOVA (electrode, phase, and cue condition) on ERN amplitudes yielded a significant main effect of electrode,  $F(2,54) = 9.22$ ,  $p < .001$ ,  $\eta_p^2 = 0.26$ , indicating that ERN amplitudes were larger at electrode FCz, than at Fz and Cz (all  $p < .003$ ), whereas amplitudes at Fz and Cz did not differ ( $p = .861$ ).

A significant main effect of phase was detected,  $F(1,27) = 5.47$ ,  $p = .027$ ,  $\eta_p^2 = 0.17$ , indicating that ERN amplitudes were smaller in the test phase than in the training phase. This effect was further specified by its interaction with electrode,  $F(2,54) = 7.18$ ,  $p = .002$ ,  $\eta_p^2 = 0.21$ , indicating that this effect was strongest at electrode Cz ( $p = .001$ ), medium at FCz ( $p = .089$ ), and absent at Fz ( $p = .415$ ). Additionally, a trend-level three-way interaction of electrode, phase, and cue condition was observed,  $F(2,54) = 3.02$ ,  $p = .057$ ,  $\eta_p^2 = 0.10$ , indicating that in the training phase, ERN amplitudes were trend-level higher in the FI condition than in the FC condition at

electrode FCz,  $t(27) = -1.95$ ,  $p = .062$ ,  $d = 0.38$ , 95% CI  $[-0.14, 0.92]$ , and Cz,  $t(27) = -1.92$ ,  $p = .065$ ,  $d = 0.39$ , 95% CI  $[-0.13, 0.93]$ , whereas no difference was observed at Fz,  $t(27) = -0.72$ ,  $p = .479$ . In the test phase, the effect of cue condition did not reach significance at any electrode (all  $p > .549$ ).

## 4 | DISCUSSION

Previous studies showed that cognitive control is flexibly adapted to task demands in healthy individuals. Adaptation of cognitive control is present on a trial-to-trial and a block level and detectable in changes of behavioral interference (response times and error rates) and medio-frontal negativities (N2, CRN, and ERN). Blockwise increase of conflict frequency results in reduced response times and error rates in incompatible trials in combination with increased N2 and reduced CRN amplitudes, indicating increased implementation of proactive stimulus-locked cognitive control (Bartholow et al., 2005; Corballis & Gratton, 2003; Grutzmann et al., 2019; Grützmann, Riesel, et al., 2014; Jiang et al., 2013; Kalanthroff et al., 2014; Wendt et al., 2008; Wendt & Luna-Rodriguez, 2009). Previous studies have demonstrated that error monitoring can be influenced by context cues (Meyer & Gawlowska, 2017; Riesel, Kathmann, Wullhorst, et al., 2019; Riesel et al., 2012). These findings indicate that participants formed a task set which included the context cues and still guided behavior although initial acquisition conditions were no longer present. In the current study, we investigated whether these effects also extend to cognitive control on correct trials, that is, interference control (N2) and postresponse strategy adaptation (CRN). Furthermore, the ERN amplitude was analyzed to explore whether previously observed conditioning of the ERN (Riesel, Kathmann, Wullhorst, et al., 2019; Riesel et al., 2012) also occurs in a purely cognitive paradigm without a punishment condition.



**FIGURE 5** Grand averages of the ERN at electrode FCz ( $\mu\text{V}$ ) in incompatible trials in the FI and FC conditions in the training phase and test phase. FC, frequent compatible; FI, frequent incompatible

In the training phase, two conflict frequency conditions were presented: one containing 25% incompatible trials (FC) and one containing 75% incompatible trials (FI). We replicated conflict-frequency-related adaptation on the behavioral and ERP levels, indicating that the task successfully modulated cognitive control activation. In line with previous studies, the 75% incompatible condition was characterized by shorter response times and reduced error rates in incompatible trials and a reduced response time congruency effect (Bartholow et al., 2005; Corballis & Gratton, 2003; Grutzmann et al., 2019; Grützmann, Riesel, et al., 2014; Jiang et al., 2013; Kalanthroff et al., 2014; Wendt et al., 2008; Wendt & Luna-Rodriguez, 2009). As expected, this was accompanied by a shift from post-response focused cognitive control to conflict-processing cognitive control, that is, increased N2 amplitudes and decreased CRN amplitudes in incompatible trials (Grutzmann et al., 2019; Grützmann, Riesel, et al., 2014). Previous research indicates that this modulation represents an adaptive mechanism of increased proactive stimulus-locked control application resulting in improved interference control (Grützmann, Riesel, et al., 2014). However, please note that the N2 does not necessarily reflect the same processes in different tasks. Previous results imply that the N2 can be divided into two anterior and one posterior subcomponent, reflecting different cognitive processes such as sequential matching, novelty, and cognitive control (Folstein & Van Petten, 2008). Thus, task-related modulations and their functional significance may vary depending on how much the respective task recruits these processes. In line with previous studies (Bartholow et al., 2005; Grutzmann et al., 2019; Grützmann, Riesel, et al., 2014), the conflict frequency effect was strongest at electrode Fz, indicating that it mainly modulated the anterior N2 related to cognitive control. Riesel and colleagues (2013) showed moderate to high convergent validity for the ERN across the flanker, Go/NoGo, and Stroop task. Until convergent validity has also been asserted for the N2, findings should be generalized with caution across different tasks. Replicating previous results of an inverse relationship between ERN amplitude and error rate (Gehring et al., 1993; Riesel, Kathmann, & Klawohn, 2019), the ERN was significantly larger in the FI than in the FC condition. As the ERN amplitude is modulated by error significance (Bartholow et al., 2012; Endrass et al., 2010; Hajcak et al., 2005), this might imply that the relatively less frequent errors under increased stimulus-locked cognitive control are subjectively more salient. Taken together, these data suggest that the participants applied different task sets characterized by distinct modes of cognitive control in the FC and FI conditions.

In the test phase, we observed no evidence for sustained conflict frequency effects. Although the stimuli

were still embedded in the context cues that were previously associated with the distinct conflict frequency conditions, response times, error rates, and medio-frontal negativities were virtually identical in the two test conditions. This pattern is in line with recent findings of Kuratomi and Yshizaki (2016) who reported evidence for fast and highly flexible adaptation of cognitive control in the flanker task. As experimental blocks were comparably long, gradual extinction could possibly reduce cue effects over time. Specifically, cue effects could only be present at the beginning of the test phase and average out, when computed across the whole condition. However, even the first block of each condition in the test phase yielded no evidence for sustained activation of the previous task set. Consequently, behavioral and ERP parameters did not differ between the first and the last block of the test phase. This shows that participants quickly adjusted processing and response strategies to the actual task requirements even in the presence of misleading cue information. This is also in line with the study of Kuratomi and Yshizaki (2016), in which a similar follow-up analysis exploring behavioral data across blocks of 48 trials within the test phase showed no differences between the blocks. Thus, similar to the present results, even in the first phase directly after training, there was no evidence for transfer of the previous task set. Taken together, the present results suggest that in healthy participants, cognitive control is quickly adapted to actual task requirements even in the presence of context cues previously associated with other response modes.

Previous behavioral studies provided evidence that cues can activate proportion congruency-related attentional adjustments. Importantly, most of these studies used task-irrelevant stimulus properties as cues (stimulus location, color, or shape, Crump et al., 2006, 2008; Crump & Milliken, 2009; Vietze & Wendt, 2009; Wendt et al., 2008). The current results imply that effects may be smaller or absent when features that are not stimulus-related serve as cues (i.e., background color). Crump and colleagues (2008) demonstrated that context cue effects on attentional adjustments are associated with attention to the predictive cue dimension. As performance in the flanker task requires a higher attention to the stimulus than to other context features (i.e., background color), this might explain why no effect was observed in the present study. Thus, we cannot distinguish whether the lack of modulation in the test phase is driven by the rapid update of the previously acquired task sets or rather due to the fact that the context cues were not integrated into the task sets in the first place. Although background colors were informative of the conflict frequency condition in the training phase, correct task processing was also possible without processing the context cues. Still, as both

processes (inhibition of task-irrelevant information, rapid update of task sets) are beneficial, the current results further underline the efficiency and flexibility of cognitive control adaptation in healthy participants.

Previous ERP studies have provided evidence for cue effects on ERN amplitude. However, in these studies, effects were only present or more pronounced for highly anxious individuals (Meyer & Gawlowska, 2017; Riesel, Kathmann, Wullhorst, et al., 2019; Riesel et al., 2012). This pattern implies altered control adaptation in individuals with high trait anxiety. Specifically, highly anxious individuals appear to stick to the task set implied by the context cues, although the environmental conditions previously associated with that cue are no longer present. In line with this, increased fear conditioning and slowed extinction have been detected in individuals with high trait anxiety (Barrett & Armony, 2009; Craske et al., 2018; Otto et al., 2007; Sehlmeier et al., 2011; Zinbarg & Mohlman, 1998) or anxiety disorders (Duits et al., 2015; Hermann et al., 2002; Lissek et al., 2005; Orr et al., 2000). Against this background, future studies should investigate the stability of cognitive control adaptation as measured by medio-frontal negativities in highly anxious individuals.

In addition to the limitations reported above, the statistical power of the study needs to be considered when interpreting the result. A post-hoc power analysis reported in detail in the Supporting Information indicated that the present design yielded adequate power (>80) to detect the effects of interest in the behavioral data and the CRN data. However, the study design was slightly underpowered for the detection of N2 effects and severely underpowered for the detection of ERN effects. Thus, the results for these two ERPs should be interpreted with caution. Based on the a priori and post-hoc power analyses, future studies addressing similar questions should use a sample of at least 40 participants especially with regard to N2 and ERN effects.

The present study explored the stability of cognitive control task sets in healthy individuals when provided with a context cue. Although typical adaptations to conflict frequency were observed in the training phase of the experiment, behavioral and ERP data provided no evidence for temporal stability of these adaptations. Instead, the present study yields further evidence for fast and efficient adaptation to actual task requirements despite misleading context cues in healthy individuals.

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## AUTHOR CONTRIBUTIONS

**Rosa Grützmann:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Writing-original draft; Writing-review & editing. **Norbert Kathmann:** Resources; Supervision; Validation; Writing-review & editing. **Stephan Heinzel:** Conceptualization; Funding acquisition; Resources; Supervision; Validation; Writing-review & editing.

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