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Control in context: The theta rhythm provides evidence for reactive control but no evidence for proactive control

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Abstract

A prime goal of psychological science is to understand how humans can flexibly adapt to rapidly changing contexts. The foundation of this cognitive flexibility rests on contextual adjustments of cognitive control, which can be tested using the list-wide proportion congruency effect (LWPC). Blocks with mostly incongruent (MI) trials show smaller conflict interference effects compared to blocks with mostly congruent (MC) trials. A critical debate is how proactive and reactive control processes drive contextual adjustments. In this preregistered study ($N = 30$), we address this conundrum, by using the theta rhythm as a key neural marker for cognitive control. In a confound-minimized Stroop paradigm with short alternating MC and MI blocks, we tested reaction times, error rates, and participants' individualized theta activity (2–7 Hz) in the scalp-recorded electroencephalogram. An LWPC effect was found for both, reaction times and error rates. Importantly, the results provided clear evidence for reactive control processes in the theta rhythm: Theta power was higher in rare incongruent compared with congruent trials in MC blocks, but there was no such modulation in MI blocks. However, regarding proactive control, there were no differences in sustained theta power between MC and MI blocks. A complementary analysis of the alpha activity (8–14 Hz) also revealed no evidence for sustained attentional resources in MI blocks. These findings suggest that contextual adjustments rely mainly on reactive control processes in the theta rhythm. Proactive control, in the present study, may be limited to a flexible attentional shift but does not seem to require sustained theta activity.

KEYWORDS
cognitive control, EEG, oscillation/time frequency analyses

1 | INTRODUCTION

Cognitive flexibility is a key human ability (Braem & Egner, 2018; Dreisbach & Fröber, 2019). A central feature of this flexibility is the ability to adapt action and thought to current context demands. Take for example the cyclist on their daily commute to work who would be more focused when riding on a two-way bicycle lane with oncoming traffic than on a one-way lane. In this example, the cognitive control demands of riding are dependent on the specific context, with higher overall cognitive demands on the two-way lane with a high frequency of oncoming riders, but specifically increased demands in case of an unexpected wrong-way rider on the one-way lane. The mechanisms underlying the adaptation of cognitive control to different contexts are still much debated. Here we utilize mid-frontal theta rhythm in the electroencephalogram (EEG) as a key neural marker of cognitive control to investigate reactive and proactive control adjustments to different contextual demands.

Experimentally, the mechanisms of cognitive control can be tested in response-conflict tasks like the color-word Stroop task (Stroop, 1935). In the standard Stroop task, participants respond to the print color of a color word, which can either be congruent or incongruent to the color indicated by the word. To investigate contextual adjustments of cognitive control, the proportion of congruent and incongruent trials (i.e., the context of the task) can be manipulated in a block-wise fashion (Lindsay & Jacoby, 1994). When comparing performance between blocks of either mostly congruent (MC) or mostly incongruent (MI) Stroop stimuli, the Stroop effect (performance difference between incongruent and congruent trials) is typically smaller in MI blocks as compared to MC blocks. This so-called list-wide proportion congruency (LWPC) effect has been demonstrated with different paradigms in different laboratories repeatedly (Abrahamse et al., 2013; Bugg & Chanani, 2011; Gonthier et al., 2016; Kane & Engle, 2003; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Spinelli & Lupker, 2021, 2022, 2023; West & Baylis, 1998; Wühr et al., 2015). Yet, the control mechanisms underlying this contextual adjustment are not fully understood.

To date, the most prominent accounts of the processes underlying the LWPC effect assume that different levels of cognitive control are involved in MC and MI blocks (Braver, 2012; Gonthier et al., 2016; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Spinelli & Lupker, 2021, 2022).[1] MI

blocks consist of a high frequency of conflict trials, in which the task-irrelevant automatic word-reading process (Brown et al., 2002) conflicts with the required color response in most trials. The most prominent view holds that the high expectancy of conflict trials leads to a strategic adjustment of top-down control, for example, heightened attentional filtering (Lindsay & Jacoby, 1994). According to this view, a proactive control mechanism reduces the processing of the irrelevant word information in advance such that the cognitive conflict does not unfold to its full extent. This is described, for example, in the influential dual mechanisms of control (DMC) theory (Braver, 2012; Braver et al., 2007). According to the DMC, two distinct mechanisms of control exist, one reactive and one proactive mechanism. A similar distinction of control was made by Ridderinkhof et al. (2011).

Proactive control describes a strategic and global process that implements top-down control prior to stimulus onset. It is an "early selection mechanism" that biases attention and perception to the task-relevant stimulus dimension (i.e., print color) in a global and sustained manner and thereby prevents or at least reduces conflict interference before it even arises (see Braver, 2012). This can be achieved by either enhancing online action control processes in advance or by reducing the need for control through increased selective attention (Ridderinkhof et al., 2011). Proactive control is often described as an expectancy-based, global, and sustained level of top-down control (active shielding). Indeed, many researchers have provided evidence that such a form of global control at the list-level is involved in the list-wide modulation of the congruency effect (Bugg et al., 2011; Bugg & Chanani, 2011; Gonthier et al., 2016; Hutchison, 2011; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979; Spinelli & Lupker, 2021, 2022; Wühr et al., 2015).

Reactive control, by contrast, is triggered by the (unexpected) conflict "just in time" and serves as a "late correction mechanism" (Braver, 2012; Braver et al., 2007). In the MC context, which represents a low-control context, responding to the color is facilitated by the irrelevant word-reading process in most cases. Accordingly, participants can adopt a relaxed control mode. Rare and unexpected conflict trials in the MC context then trigger reactive control in terms of an immediate, stimulus-driven upregulation of cognitive control in response to the experienced conflict interference. In MI lists, the engagement of proactive control reduces the need for reactive control (Ridderinkhof et al., 2011).

The DMC framework makes clear predictions about the involved brain areas behind reactive and proactive control. Both reactive and proactive control have been linked to the prefrontal–parietal control network, comprising the anterior cingulate cortex (ACC), the dorsolateral prefrontal cortex (dlPFC), as well as superior and inferior parietal regions (Braver, 2012; Braver et al., 2007). The interactions between ACC as

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[1]The LWPC effect has also been accounted for without assuming an involvement of cognitive control (Schmidt, 2021, 2013a, 2013b, 2019). Therefore, when aiming to address cognitive control mechanisms in the LWPC effect, a number of precautions have to be considered in the experimental paradigm (see Braem et al., 2019; Section 2).

a specialized conflict detection module and dlPFC as a control module biasing task-relevant and -irrelevant processing, serve central functions in the processing of conflict (Badre & Wagner, 2004; Botvinick et al., 2001, 2004; Kerns et al., 2004; Liu et al., 2008; Morishima et al., 2010; Pisapia & Braver, 2006).

Accordingly, in LWPC studies using functional magnetic resonance imaging (fMRI), reactive control in response to rarely occurring conflicts in MC contexts leads to heightened transient neural activation in the ACC and other areas of the fronto-parietal control network for incongruent (compared with congruent or neutral) trials (Carter et al., 2000; Grandjean et al., 2012; Wilk et al., 2012). For proactive control, the DMC framework predicts active shielding in the form of heightened global and sustained activity in the dlPFC in MI compared with MC contexts (Braver et al., 2007). However, analogous fMRI findings that show sustained activity in the dlPFC (Aben et al., 2019; Pisapia & Braver, 2006) are sparse. By contrast, many studies could not provide clear evidence for sustained control in the form of heightened lateral prefrontal cortex (PFC) activity in MI blocks (Blais & Bunge, 2010; Grandjean et al., 2012; Wilk et al., 2012). This raises the question to what extent and in what form proactive control, in the sense of active shielding and sustained control, is involved in LWPC effects at all. Taken together, while the assumption of a reactive control mechanism seems plausible and has received much empirical support for the processing of infrequent conflict trials in the MC context, the question of how proactive control contributes to the processing of frequent conflict trials in the MI context remains largely unclear.

One major limitation of fMRI studies lies in their poor temporal resolution. Contextual adjustments of cognitive control can happen rather quickly. Therefore, the precise temporal resolution of electroencephalography (EEG) may provide a better means to understand the flexible dynamics of proactive and reactive control. To that end, the present study investigated 2–7 Hz theta-band oscillations in the EEG frequency band as a comprehensive measure of cognitive control.

The mid-frontal 2–7 Hz theta rhythm has been characterized as a key neural measure of cognitive control in various scenarios (e.g., novelty, conflict, punishment, and errors; for reviews, see Cavanagh & Frank, 2014; Cohen, 2014). In these studies, theta power was consistently increased in response to conflict (Cohen & Donner, 2013; Giller et al., 2020; Haciahmet et al., 2023; Hanslmayr et al., 2008). Therefore, theta power may reflect reactive modulations of cognitive control in the Stroop paradigm. Furthermore, multiple studies demonstrated that theta power is also associated with cue-triggered proactive control processes (Cooper et al., 2015, 2017, 2019; De Loof et al., 2019; Eisma et al., 2021; Eschmann et al., 2018). For example, theta power is larger when proactively preparing for a harder task (De Loof et al., 2019) or when proactively maintaining critical cue information (Eschmann et al., 2018). Beyond these cue-driven proactive adjustments, there are findings about increased sustained theta in response to a higher working memory load (Jensen & Tesche, 2002). Therefore, the theta rhythm reflects a global marker of human cognitive control (Köster, 2024), but it has not yet been applied to measure contextual adjustments of control. Here, we used theta rhythm to assess the within-trial adjustments of reactive control as well as sustained proactive control processes, the active shielding, which may vary between MI and MC blocks in the LWPC paradigm.

In this preregistered EEG study, we used theta rhythm for the first time to dissociate the involvement of reactive versus proactive control mechanisms in flexible contextual processing adjustments. To this end, we manipulated the LWPC in short blocks of 20 trials using a confound-minimized Stroop paradigm (see Methods) while recording the EEG. Critically, each block started with four context-typical trials (incongruent in the MI block, congruent in the MC blocks). This ensured that participants would receive a strong context signal at the beginning of each block, which should ease the respective contextual adjustments. More precisely, the repeated experience of congruent stimuli at the beginning of MC blocks should lead to relaxation and enhance the usage of the irrelevant word information, whereas the repeated experience of incongruent stimuli at the beginning of MI blocks should increase active shielding and reduce reliance on the irrelevant word information. Behaviorally, we expected to find the typical LWPC effect in terms of a smaller congruency effect in MI blocks as compared to MC blocks. On the trial level, we expected more theta activity in incongruent trials in MC blocks as compared to MI blocks indicating increased reactive control. A generally more sustained prefrontal theta activity in MI compared with MC blocks was hypothesized to indicate increased proactive control.

2 | METHOD

2.1 | Participants

The present study was preregistered (https://aspre dicted.org/e4v46.pdf). Accordingly, 30 participants ($M_{age} = 22.67$ years, $SD = 2.67$, range 18–29 years; 26 female, four male; 27 right-handed, three left-handed) were assessed to obtain a final sample size of at least 28

(cf. Grandjean et al., 2012). However, all participants were included in the final sample. Most previous studies investigating theta power and cognitive control used smaller sample sizes and yielded reliable effects (Cooper et al., 2015; De Loof et al., 2019; Hanslmayr et al., 2008; Jensen & Tesche, 2002). To be on the safe side, we chose a larger sample size and, in the preregistration, included the rule to use Bayesian sequential testing in the case that the results would not be clear. Participants received course credit or monetary compensation (8 €/h) for completing the experiment. All participants gave informed consent prior to the beginning of the experiment.

2.2 | Tasks and stimuli

The stimuli of the Stroop task were implemented with the German color words (Calibri, 50 pt) "ROT" (red), "BLAU" (blue), "GELB" (yellow), "GRÜN" (green) printed in red (RGB: 255, 0, 0), blue (RGB: 0, 0, 255), yellow (RGB: 255, 255, 0), or green (RGB: 0, 128, 0) on a gray background (RGB: 128, 128, 128). The combinations were manipulated in pairs so that the words red or blue could only appear in red or blue ink and the words yellow and green only in yellow or green ink.[2] In every trial, participants had to respond to the print color by pressing the keys C, V, N, or M on a QWERTZ keyboard. One color pair was mapped to the left hand (e.g., pressing C for red and V for blue ink) while the other pair was mapped to the right hand (e.g., pressing N for yellow and M for green ink). The hand-to-color mapping was counterbalanced across participants. The experiment was programmed in E-Prime 2.0 (Psychology Software Tools, Sharpsburg, USA) and displayed on an LED Monitor (19″, 1280 × 1024 px, 60 Hz).

2.3 | Procedure

First, participants completed 10 plates of the Ishihara (1918) test for color blindness to ensure functional color vision. All participants passed the color vision test. Then, the experiment started with 24 eye-movement trials where participants had to follow a fixation cross, moving from the center of the screen to the left, right, up, or down, and 12 eye blink trials. These trials were included to facilitate eye-movement detection using independent component analysis (ICA; see EEG analysis).

In the first practice block, the mapping of the four print colors to response keys was instructed and trained by using colored squares (20 trials). In the second practice block, instead of squares, color words were presented in congruent or incongruent print colors (40 trials). The main experiment consisted of 30 blocks with 20 trials each. 15 MC (16 congruent trials, 4 incongruent trials) and 15 MI blocks (16 incongruent trials, 4 congruent trials) alternated, while the first block always contained MC trials to avoid the asymmetric list shift effect (cf. Abrahamse et al., 2013). To provide a strong (implicit) context signal, the first four trials always belonged to the frequent condition. Participants were not instructed about the different block types. The color pair alternated each trial in order to avoid the effects of negative priming (Braem et al., 2019). Therefore, the task-relevant and irrelevant features of the stimulus (color and word) together with the response hand changed on every trial. After each block, there was a self-paced break of at least 10 seconds.

Each trial started with a fixation cross in the center of the screen for 500 ms. Next, the target appeared until a response was given. Feedback was only presented after errors in form of the German word "Fehler!" (Error!) in black ink for 1000 ms. Last, the duration of the inter-trial interval was jittered (1000, 1050, 1100, 1150, or 1200 ms).

2.4 | Design

A repeated-measures design with the factors Proportion Congruency (MC, MI) x Congruency (congruent, incongruent) was used. The dependent measures were participants' reaction time (RT in ms), error rate (in %), and trials-wise mid-frontal theta power. In addition, sustained theta power was tested as the baseline activity of the MC and MI block trials.

2.5 | Behavioral data preprocessing

In all analyses, we followed the preregistered protocol unless explicitly indicated otherwise. Before analyzing the error rates, the first trial of each test block was excluded (5% of all trials). For the analysis of RTs, the additional exclusion of error trials (5.27%), trials following errors (4.97%), RTs shorter than 250 and larger than 8000 ms (0.13%), and RTs more than three standard deviations above or below the individual cell mean (1.51%). No participant had to be excluded due to overall error rates or RTs with more than three interquartile ranges above the third or below the first quartile, indicating that all participants were focused on the task.

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[2]This color pair mapping was not counterbalanced because there is no potential confounding effect of the colors on the present research question. However, individual colors were roughly equally distributed across the different design cells.

2.6 | EEG recordings and preprocessing

EEG was recorded from 64 Ag/AgCl active electrodes positioned according to the extended international 10–20 system (actiCAP, Brain Products, Gilching, Germany). FCz served as the online reference, and the AFz electrode served as the ground electrode. The sampling rate was set to 500 Hz and impedances were kept below 25 kΩ during the recording.

For the preprocessing of the EEG data, MATLAB (R2022a, The MathWorks Inc., Natick, Massachusetts) and the EEGLAB toolbox (Delorme & Makeig, 2004) were used. A high-pass (cutoff: 1) and low-pass filter (cutoff: 100 Hz) were applied, and the data were segmented from −1000 to 1500 ms with regard to the stimulus onset. Noisy trials were removed based on visual inspection. Furthermore, eye-movement and muscle artifacts were removed manually, using ICA. On average, 5.25% ($SD = 3.61\%$) of segments were excluded per participant (range: 2.33%–15.50%), resulting in an average of 568.50 (of the initial 600) trials that were available for each participant.

Spectral changes in oscillatory activity were assessed using Morlet's wavelet transform, Morlet parameter $m = 7$ (Bertrand & Pantev, 1994). The spectral activity was first calculated for each trial and then averaged across the trials of the different conditions, to obtain the total spectral activity, not tightly locked to stimulus onset (Tallon-Baudry & Bertrand, 1999).

The individual theta frequency (here defined as the frequency with the highest increase in theta power relative to the baseline; cf. Friese et al., 2013; Köster et al., 2018; Köster et al., 2014; Köster et al., 2019) was identified between 2 and 7 Hz between 400 and 800 ms at the peak electrodes (Cz and its 8 surrounding electrodes, see pre-registration), resulting in an average individual theta frequency of 3.75 ($SD = 1.28$). (Note that the time window analyzed here and all subsequent analyses differ from the preregistered time window [i.e., 0–500 ms]. This was due to the observed grand mean theta peak in this time range, see Figure 2a, which is very similar to the theta peak observed in a former study; Hanslmayr et al., 2008).

For the total theta response, a baseline correction was applied to obtain the relative signal change, calculated as the percent of signal change with regard to a −500 to −200 ms baseline (not extending until 0 to avoid edge artifacts; cf. Köster et al., 2018; Köster et al., 2019). For all analyses, the electrode with the peak theta response at central recording sites and its direct neighbors was selected. For the analyses of the theta response, the time window from 400 to 800 ms was used, according to the grand mean activity (Figure 2a).

For the sustained theta power, to include as much preparatory activity as possible without interference from the current target or the previous trial, we used the data of the fixation interval (−500 to −200 ms, to avoid edge effects), without applying any baseline correction, for MC and MI blocks separately. That is, the overall theta power in the fixation interval should be different between the MC and MI blocks in case of active shielding, a sustained proactive control in the MI context. Note that we preregistered to analyze the sustained activity during the extended time window of −500 to 1000 ms. However, this would also include any reactive control processes, and therefore we considered the baseline activation more appropriate. For completeness, the results for the preregistered analyses are provided within the Data S1.

3 | RESULTS

3.1 | Behavioral results

3.1.1 | Error rates

The 2 Proportion Congruency (MC, MI) ×2 Congruency (congruent, incongruent) repeated-measures ANOVAs of the error rates revealed the significant main effects of Proportion Congruency, $F(1, 29) = 4.46$, $p = .044$, $\eta_p^2 = .13$, $BF_{10} = 0.734$, and Congruency, $F(1, 29) = 11.67$, $p = .002$, $\eta_p^2 = .29$, $BF_{10} = 21.417$. Error rates were larger in MC blocks ($M = 6.32\%$, $SD = 3.30$) compared with MI blocks ($M = 5.41\%$, $SD = 3.97$), and in incongruent ($M = 7.22\%$, $SD = 4.31$) compared with congruent trials ($M = 4.51\%$, $SD = 3.83$). In line with the typical LWPC effect, these main effects were further qualified by a significant interaction between Proportion Congruency and Congruency, $F(1, 29) = 5.20$, $p = .030$, $\eta_p^2 = .15$, $BF_{10} = 4.119$ (see Figure 1a). The interaction was due to a larger Congruency effect in MC blocks ($M_{congruent} = 4.42\%$, $SD = 3.76$; $M_{incongruent} = 8.22\%$, $SD = 4.59$; $M_{difference} = 3.81\%$, $SD = 5.18$), $t(29) = 4.03$, $p < .001$, $d = 0.74$, $BF_{10} = 79.819$, compared with a non-significant Congruency effect in MI blocks ($M_{congruent} = 4.61\%$, $SD = 4.39$; $M_{incongruent} = 6.21\%$, $SD = 4.97$; $M_{difference} = 1.60\%$, $SD = 4.98$), $t(29) = 1.76$, $p = .090$, $d = 0.32$, $BF_{10} = 0.758$. The error rates on incongruent trials were larger in MC blocks compared with MI blocks, $t(29) = 2.66$, $p = .013$, $d = 0.49$, $BF_{10} = 3.723$. On congruent trials, the difference between block types was not significant, $t(29) = 0.38$, $p = .707$, $d = 0.07$, $BF_{10} = 0.208$.

3.1.2 | Reaction times

The 2 Proportion Congruency (MC, MI) ×2 Congruency (congruent, incongruent) repeated-measures ANOVAs of the RTs resulted in the significant main effect of Congruency,
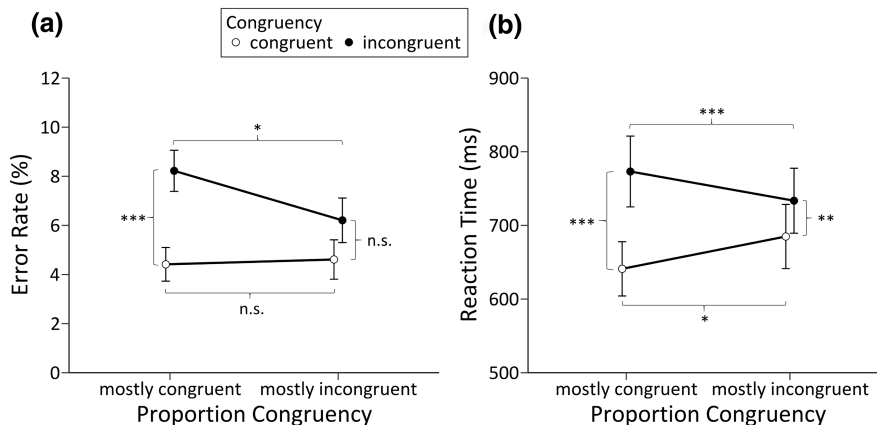
FIGURE 1 Error rate (%; a) and reaction times (ms; b) as a function of Proportion Congruency (mostly congruent, mostly incongruent) and Congruency (congruent, incongruent). Error bars represent ± one standard error of the mean. Brackets indicate post hoc t-tests following significant interactions (error rates: $F(1, 29) = 5.20$, $p = .030$, $\eta_p^2 = .15$, $BF_{10} = 4.119$; reaction times: $F(1, 29) = 22.46$, $p < .001$, $\eta_p^2 = .44$, $BF_{10} = 2.146 \times 10^3$). ***$p < .001$, **$p < .010$, *$p < .050$; n.s., non-significant.

$F(1, 29) = 49.12$, $p < .001$, $\eta_p^2 = .63$, $BF_{10} = 1.093 \times 10^5$, with shorter RTs on congruent ($M = 663$ ms, $SD = 216$) compared to incongruent trials ($M = 753$ ms, $SD = 251$). The main effect of Proportion Congruency did not reach significance, $F(1, 29) = 0.04$, $p = .848$, $\eta_p^2 < .01$, $BF_{10} = 0.237$. Furthermore, the interaction between Proportion Congruency and Congruency was significant, $F(1, 29) = 22.46$, $p < .001$, $\eta_p^2 = .44$, $BF_{10} = 2.146 \times 10^3$ (see Figure 1b). This interaction was explained by a larger Congruency effect in MC blocks ($M_{congruent} = 641$ ms, $SD = 202$; $M_{incongruent} = 773$ ms, $SD = 263$; $M_{difference} = 132$ ms, $SD = 92$), $t(29) = 7.84$, $p < .001$, $d = 1.43$, $BF_{10} = 1.101 \times 10^6$, compared with MI blocks ($M_{congruent} = 685$ ms, $SD = 238$; $M_{incongruent} = 734$ ms, $SD = 242$; $M_{difference} = 49$, $SD = 56$), $t(29) = 3.40$, $p = .002$, $d = 0.62$, $BF_{10} = 18.233$. Furthermore, RTs on incongruent trials were larger in MC blocks compared with MI blocks, $t(29) = 3.86$, $p < .001$, $d = 0.71$, $BF_{10} = 53.880$. Conversely, RTs on congruent trials were larger in MI blocks compared with MC blocks, $t(29) = 2.58$, $p = .015$, $d = 0.47$, $BF_{10} = 3.189$.

3.2 | Neural activity

The time-frequency analysis revealed typical changes in response to the stimulus onset, as depicted in Figure 2a. The grand mean activity across all electrodes was increased in the theta range (2–7 Hz), while alpha band (8–14 Hz) amplitudes were decreased. The corresponding topography is depicted in Figure 2b.

3.2.1 | Theta activity

The 2 Proportion Congruency (MC, MI) x 2 Congruency (congruent, incongruent) repeated-measures ANOVA of theta activity (400 to 800 ms; reactive control) resulted in a significant main effect of Congruency, $F(1, 29) = 10.90$, $p = .003$, $\eta_p^2 = .27$, $BF_{10} = 5.177$, with larger theta power on incongruent ($M = 0.28$, $SD = 0.12$) compared with congruent trials ($M = 0.23$, $SD = 0.11$). The main effect of Proportion Congruency did not reach significance, $F(1, 29) = 4.02$, $p = .054$, $\eta_p^2 = .12$, $BF_{10} = 0.655$. Most importantly, there was a significant interaction between Proportion Congruency and Congruency, $F(1, 29) = 36.22$, $p < .001$, $\eta_p^2 = .56$, $BF_{10} = 1.226 \times 10^6$. The Congruency effect of trial-wise theta power was larger in MC blocks ($M_{congruent} = 0.20$, $SD = 0.10$; $M_{incongruent} = 0.34$, $SD = 0.17$; $M_{difference} = 0.14$, $SD = 0.14$), $t(29) = 5.66$, $p < .001$, $d = 1.03$, $BF_{10} = 4.808 \times 10^3$, compared to the non-significant Congruency effect in MI blocks ($M_{congruent} = 0.25$, $SD = 0.14$; $M_{incongruent} = 0.22$, $SD = 0.10$; $M_{difference} = -0.03$, $SD = 0.10$), $t(29) = 1.54$, $p = .135$, $d = 0.28$, $BF_{10} = 0.559$ (see Figure 2c,d). Because theta power is typically increased in response to errors, we repeated the analysis only including correct trials to avoid this potential confound. The critical interaction was still significant ($p < .001$, $BF_{10} = 9.227 \times 10^5$; see Data S1).

The paired-sample t-test of sustained theta power (-500 to -200 ms, without taking a baseline; proactive control) between MC ($M = 19.86$, $SD = 5.10$) and MI blocks ($M = 19.74$, $SD = 4.92$) was not significant, $t(29) = 0.71$, $p = .241$, $d = 0.13$, $BF_{10} = 0.245$ (see Figure 3a; see Data S1 for the analysis of sustained theta power in a larger time window -500 to 1000 ms). The Bayes Factor indicates moderate evidence for the null hypothesis (Lee & Wagenmakers, 2014). In the plot, a descriptive difference in sustained theta power between MC and MI blocks is evident in a later time window (500–1000 ms). Given that this activity happened after the mean response and may, therefore, also reflect the effects of different response
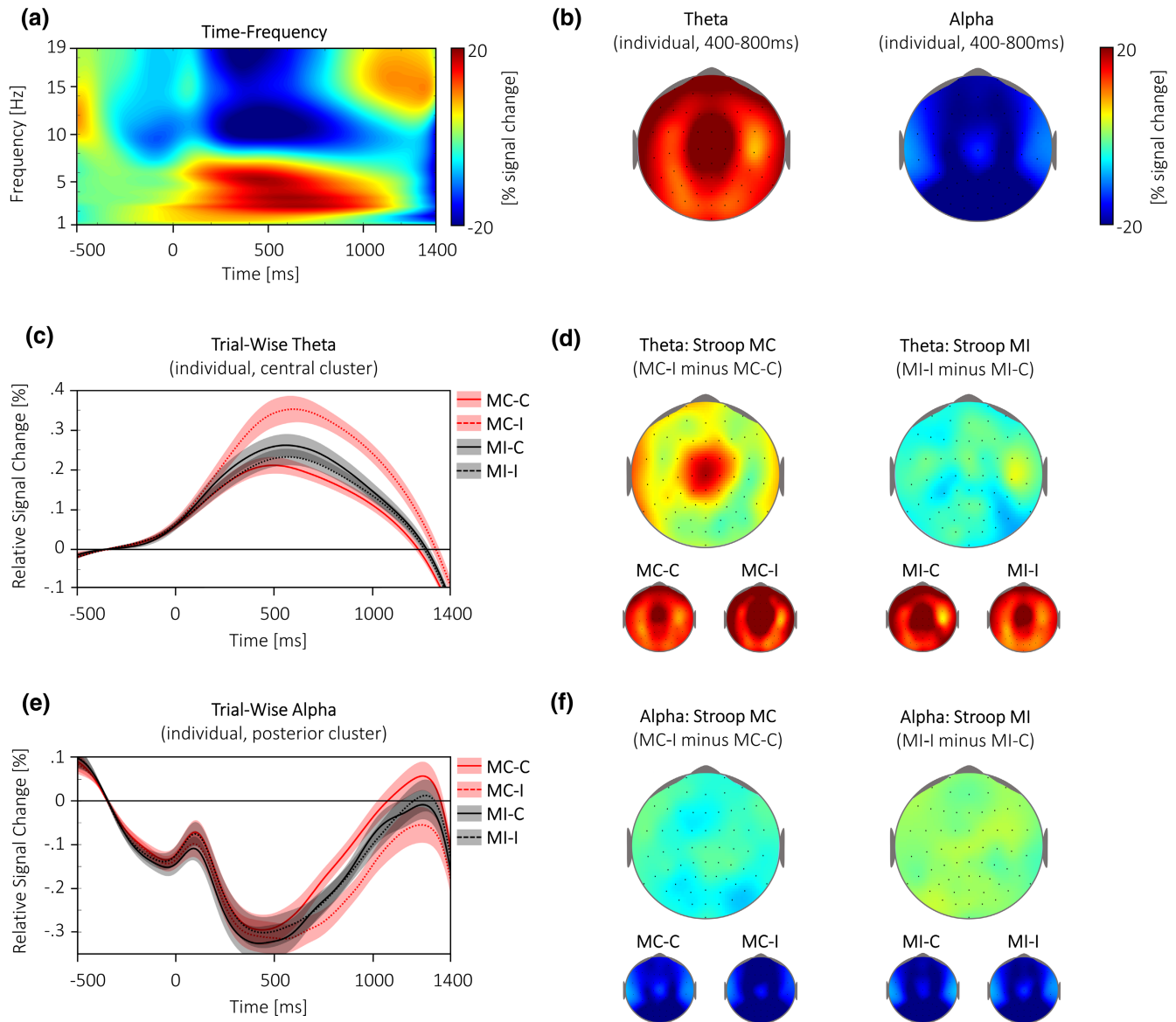
FIGURE 2 Time–frequency plot of the grand mean spectral activity at central electrodes (a), topography of theta and alpha activity (b), time course and topography of trial-wise theta (c and d), and alpha activity (e and f) per Proportion Congruency (mostly congruent, mostly incongruent) and Congruency (congruent, incongruent). The analyzed time window of trial-wise theta and alpha activity was 400–800 ms.
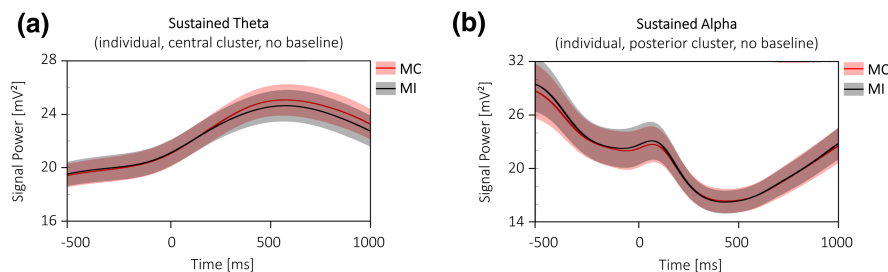

FIGURE 3 Time course of sustained theta (a) and alpha (b) activity per Proportion Congruency (mostly congruent, mostly incongruent). The analyzed time window of sustained theta and alpha activity was −500 to −200 ms. Additional analyses of sustained theta and alpha activity in a larger time window (−500 to 1000 ms) are reported in the Data S1.

times, we did not further analyze this. Additionally, because proactive control might be especially pronounced at the beginning (the first trial) of each, we also analyzed sustained theta on the first trial in blocks 6–30. At this point, the participants were familiar with the general block structure and could potentially engage in preparatory proactive control. However, there was no significant difference between MC and MI blocks ($p = .345$, $BF_{10} = 0.296$; see Data S1). Additionally, to substantiate this finding, we checked whether any of the 64 electrodes showed a significant difference in sustained theta power between MC and MI blocks. This whole-brain-analysis confirmed the present pattern of results (all $ps \geq .075$, $t(29) \leq 1.85$; see Data S1).

3.2.2 | Exploratory analyses of alpha activity

Besides the theta rhythm, a reduction in the posterior 8–14 Hz alpha rhythm (alpha suppression) has formerly been associated with sustained attention processes, for example, in working memory paradigms (Foster et al., 2017; Jensen et al., 2002; Köster & Gruber, 2022). Therefore, we additionally conducted exploratory analyses of the alpha rhythm. The individual alpha peak (suppression) was identified over all posterior channels (Pz, P1-P8, PO3, PO4, PO7, PO8, Oz, O1, O2, Iz), as the frequency with the highest suppression between 8 and 14 Hz. This resulted in an average individual alpha frequency of 10.82 ($SD = 1.63$). For the trial-wise and sustained alpha analyses, we used the same preprocessing procedure and time windows as in the analyses of theta power.

The 2 Proportion Congruency (MC, MI) × 2 Congruency (congruent, incongruent) repeated-measures ANOVA of trial-wise alpha activity (400 to 800 ms) resulted in a significant main effect of Congruency, $F(1, 29) = 11.61$, $p = .002$, $\eta_p^2 = .29$, $BF_{10} = 3.036$, with larger alpha suppression on incongruent trials ($M = -0.29$ $SD = 0.17$) than on congruent trials ($M = -0.27$, $SD = 0.16$). The main effect of Proportion Congruency was not significant, $F(1, 29) = 0.74$, $p = .396$, $\eta_p^2 = .03$, $BF_{10} = 0.274$. Furthermore, the interaction between Proportion Congruency and Congruency was significant, $F(1, 29) = 22.83$, $p < .001$, $\eta_p^2 = .44$, $BF_{10} = 9.443 \times 10^4$. This interaction was explained by a larger Congruency effect in MC blocks ($M_{congruent} = -0.25$, $SD = 0.16$; $M_{incongruent} = -0.30$, $SD = 0.17$; $M_{difference} = 0.05$, $SD = 0.05$), $t(29) = 5.56$, $p < .001$, $d = 1.01$, $BF_{10} = 3.703 \times 10^3$, compared with the non-significant Congruency effect in MI blocks ($M_{congruent} = -0.29$, $SD = 0.18$; $M_{incongruent} = -0.27$, $SD = 0.17$; $M_{difference} = -0.02$, $SD = .05$), $t(29) = 1.49$, $p = .146$, $d = 0.27$, $BF_{10} = 0.527$ (see Figure 2e,f). The paired test for sustained alpha power (-500 to -200 ms, without taking a baseline) showed no significant difference between

MC ($M = 25.69$, $SD = 13.38$) and MI blocks ($M = 26.17$, $SD = 13.54$), $t(29) = 1.62$, $p = .058$, $d = 0.30$, $BF_{10} = 0.623$ (see Figure 3b; see the Data S1 for the analysis of sustained alpha power in a larger time window -500 to 1000 ms).

4 | DISCUSSION

The current study aimed to examine the underlying mechanisms of contextual adjustments of cognitive control using the theta rhythm in the EEG as a key neural marker of cognitive control. To this end, participants worked through short blocks of either MC or MI Stroop tasks. We found clear evidence for contextual adjustments of cognitive control as shown by the typical LWPC effect in error rates and RTs: We observed larger congruency effects in MC blocks compared to MI blocks even with short blocks and frequent switches between MI and MC contexts in a confound-minimized design. Consistent with previous studies, performance was particularly impaired on rare incongruent trials in MC blocks (Abrahamse et al., 2013; Gonthier et al., 2016; Lindsay & Jacoby, 1994; Logan & Zbrodoff, 1979). Critically, we found clear evidence for reactive control indicated by increased mid-frontal theta power in response to incongruent compared to congruent trials in MC, but not in the MI blocks. However, our data did not reveal any evidence for sustained proactive control processes differing between MC and MI blocks, neither in the sustained theta band nor in the adjacent alpha band. Overall, there is a sustained theta signal evident in preparation for the target. However, this can only be interpreted as relative control engagement when comparing different conditions. The results thus provide clear evidence that reactive control directly contributes to the LWPC effect and substantiate that the theta rhythm is a solid marker of reactive control (Capizzi et al., 2020).

The present results revealed reactive adjustments in trial-wise theta power. In line with the conflict monitoring theory (Botvinick et al., 2001) and the dual mechanisms of control framework (Braver, 2012), a flexible (reactive) upregulation of cognitive control is only necessary in MC blocks once a rare conflict arises. In the present study, this reactive control was evident in increased mid-frontal theta power in rare incongruent trials in MC blocks. In MI blocks, attention is shifted toward the relevant stimulus dimension, and there is little need for reactive control in incongruent trials since incongruent information is not utilized. This assumption is supported by the present finding that mid-frontal theta power was not increased for incongruent trials compared with congruent trials in the MI blocks. Importantly, our findings show that these modulations do not merely reflect reactions to item (in) frequency. If that had been the case, the results should

have shown significantly increased theta power for the rare congruent items in MI blocks, too. This reactive adjustment of control was also evident in alpha power. In MC blocks, the unexpected conflicts elicited a larger alpha suppression. This is in line with previous studies showing that alpha suppression is increased in response to conflict (Asanowicz et al., 2021; Bacigalupo & Luck, 2019).

Testing proactive control processes by analyzing the sustained theta activity between trials of the MC and MI trials, we did not find any differences between these blocks. This lack of sustained control processes in the theta rhythm is in contrast to the concept of Botvinick et al. (2001). They state that the conflict signal should be cumulatively increased in the MI block necessitating a sustained control mechanism to account for the high number of incongruent stimuli. Similar to the present results, Grandjean et al. (2012) did not find any signs of sustained proactive control in the lateral PFC during the LWPC manipulation (but see Aben et al., 2019). The advantage of the present study over previous fMRI studies is the high temporal resolution of EEG to uncover the underlying processes of contextual adjustments of control. By investigating established neural measures for active and sustained monitoring, that is, theta activity (Jensen & Tesche, 2002), and sustained attention, that is, alpha activity (Foster et al., 2017; Jensen et al., 2002; Köster & Gruber, 2022), we found no evidence for sustained proactive control in form of active shielding in both measures. Ridderinkhof et al. (2011) argued that proactive control can be achieved by either enhancing action control or increasing selective attention. However, there were no indications of such sustained processes in theta or alpha power. Of course, the absence of sustained control in theta and alpha power should be interpreted with caution as proactive control may still be engaged through other pathways.

The present findings show that the processes behind contextual control adjustments may be different from what prominent theories have suggested. Theta and alpha power did not show any indication of proactive sustained control through active shielding in the MI context. Still, the Stroop effect was essentially eliminated in RTs and error rates, clearly indicating that participants successfully adjusted to the changing contextual demands. But how did participants adjust to the frequently occurring incongruent stimuli in MI blocks? Braver (2012) argued that proactive control biases attention toward the relevant stimulus dimension (i.e., the print color), reduces conflict interference, and thereby the need for control in MI blocks. In the present design, the first four trials of each block, which were always of the frequent congruency type (congruent in MC blocks; incongruent in MI blocks; similar to Grandjean et al., 2012), may have

helped to establish the current context rather quickly. In other words, entering a stable MI context may have resulted in a fast adjustment of processing incongruent trials. More precisely, due to the lack of congruent stimuli in the first four trials of the MI block, the experience of a facilitating word-reading process is missing. This may ease an attentional shift toward the color feature which makes incongruent trials less likely to be registered as conflict resulting in the current behavioral and neurophysiological findings. Furthermore, because the context alternated predictably after each block, participants might have been able to adjust to the following context rather efficiently. In line with this assumption, we did not find active shielding indicated by increased sustained theta or alpha power in MI blocks, because cognitive control was actually not increased over the entire block. Additionally, note that Braver (2012) described proactive control as a resource-demanding process. However, the present shift in the mental configuration did not appear to be cognitively demanding as theta power was not increased during MI blocks. Taken together, the present results indicate that the mechanism behind control adjustments in MI blocks might represent a simple shift in attention toward the relevant stimulus dimension or the retrieval of the appropriate control set once the MI context is encountered (Bugg & Crump, 2012).

One might argue that theta power does not reflect a suitable measure of sustained proactive control (active shielding). However, previous studies have shown that theta oscillations are associated with proactive control when preparing for a cued task switch (Cooper et al., 2015, 2017, 2019), when preparing for cued task difficulty (De Loof et al., 2019), when maintaining the cue in an AX-continuous performance task (Eisma et al., 2021), or in a delayed match-to-sample task (Eschmann et al., 2018). The characteristics of the proactive control necessary in the LWPC manipulation might be different from these moment-to-moment increases in proactive control. However, there are also clear indications that sustained theta and alpha activity can reflect proactive control when adjusting to the current working memory load (Jensen et al., 2002; Jensen & Tesche, 2002). Accordingly, the present study should have revealed such sustained processes either in theta power (active monitoring, higher cognitive demand) or in alpha power (sustained attention) in the LWPC manipulation which did not seem to be the case. Specifically, the theta and the alpha range represent the most commonly investigated oscillatory signatures with regard to cognitive control (Capizzi et al., 2020; Cohen & Donner, 2013; Cooper et al., 2015, 2017, 2019; De Loof et al., 2019; Eschmann et al., 2018; Foster et al., 2017; Haciahmet et al., 2023; Hanslmayr et al., 2008; Jensen et al., 2002; Jensen & Tesche, 2002). Taken together, the

absence of increased sustained theta power in MI blocks, together with the established phenomenology of sustained theta power in cognitive control paradigms, challenges previous perspectives on the nature of proactive control.

Instead of the present list-wide approach to proactive control, other EEG studies investigated the explicit cueing of control from trial to trial. Some studies found evidence for proactive control in the form of increased mid-frontal theta power in response to conflict cues (Asanowicz et al., 2022; van Driel et al., 2015; but see Kaiser & Schütz-Bosbach, 2019). The lack of sustained theta power in MI blocks suggests that context-specific control adjustments in the present study are conceptually different from these trial-by-trial increases in control. Block-wise control adjustments may primarily involve an attentional shift and appear to be less demanding whereas trial-by-trial conflict cues may trigger preemptive control processes in line with previous theoretical work (Braver, 2012; Ridderinkhof et al., 2011).

It is important to note, that the present study used a confound-minimized Stroop paradigm, avoiding the effects of negative priming, with rather short blocks with MC and MI trials. The behavioral results showed a clear LWPC effect with a larger congruency effect in MC blocks. This implies that the cognitive system can shift between control states rather effortlessly. At first glance, this is at odds with the asymmetrical list-shifting effect found by Abrahamse et al. (2013). They showed that shifts from MI to MC lists led to a much smaller change in the magnitude of the Stroop effect compared to shifts from MC to MI lists. When coming from a more shielded control state after an MI block, it is harder to detect the now helpful irrelevant word dimension in MC blocks. By contrast, coming from a more relaxed control state after an MC block, the interference by the incongruent trials in the MI block is quickly detected. So, the fact that we did *not* find any evidence for this asymmetric list shift effect might in part also explain why we did not find any evidence for the involvement of sustained proactive control. This inconsistency might be explained by the methodological aspects of the current study mentioned above: (1) The first four trials of each block belonged to the frequent congruency condition thereby sending a strong context signal, and (2) the context alternated predictably after each block. This might have made the context change more obvious to the participants and facilitated control adjustments, therefore resulting in the observed large LWPC effect. Future studies should further investigate different factors that can modify the ease of control adjustments.

In conclusion, this study investigated contextual adjustments of cognitive control. We found no evidence for the involvement of proactive control (active shielding) as indexed by sustained theta power in blocks with mostly incongruent Stroop stimuli. This suggests that—at least with strong context signals—a shift of attention toward the relevant stimulus dimension may be facilitated, thus reducing the requirement of sustained proactive control in lists with mostly incongruent trials, at least as far as it can be measured by sustained theta power. Reactive control, as measured by trial-wise theta power, was consistently increased in response to rare conflicts in MC blocks. In sum, the results provide strong evidence for the contribution of reactive control but no evidence for sustained proactive control in the theta rhythm during contextual adjustments of cognitive control.

AUTHOR CONTRIBUTIONS
Jonathan Mendl: Conceptualization; data curation; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing. **Sayani Banerjee:** Data curation; formal analysis; investigation. **Rico Fischer:** Conceptualization; methodology; writing – review and editing. **Gesine Dreisbach:** Conceptualization; methodology; resources; supervision; writing – review and editing. **Moritz Köster:** Conceptualization; formal analysis; methodology; resources; supervision; visualization; writing – review and editing.

DATA AVAILABILITY STATEMENT
Raw data files associated with this article can be found online under the following link: https://osf.io/tz7q5/?view_only=99d31dd420584be8ae501ab13862ee40. The experiment was preregistered: https://aspredicted.org/e4v46.pdf. Additional study materials (e-prime file, analysis scripts) will be shared upon request. For all Bayesian analyses, JASP version 0.18.3.0 was used with its preset parameters, default priors, and the repeatability seed 123 (van Doorn et al., 2021). In the Data S1, we reported additional exploratory analyses of trial-wise theta power using only correct trials, sustained theta and alpha power in a larger time window, sustained theta power using only the first trial of blocks 6–30, a whole-brain analysis of sustained theta power, and congruency sequence effects on error rates, RTs, and trial-wise theta power. The overall pattern of the results remained the same and congruency sequence effects did not influence the present findings.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Data S1. Supplemental material.