

Theta-band Connectivity within Cognitive Control Brain Networks Suggests Common Neural Mechanisms for Cognitive and Implicit Emotional Control

Agnieszka K. Adamczyk^{1,2}  and Mirosław Wyczesany² 

Abstract

■ Self-control is a core aspect of adaptive human behavior. It allows the attainment of personal goals by regulating unwanted thoughts, emotions, and behavior. Previous research highlighted the crucial role of cognitive control for explicitly pursued self-control and explicit emotion regulation strategies (such as cognitive reappraisal or attentional distraction). The present study investigated whether similar neural mechanisms would be involved in an implicit self-control task that acted as a covert emotion regulation strategy. Thirty-six female participants unscrambled sentences of either neutral (no-regulation condition) or neutral and self-control-related content (regulation condition) before passively viewing negative and neutral pictures. Compared with the no-regulation condition, implicit induction of self-control reduced the amplitude of the late positive potential to negative pictures, indicating successful emotion downregulation. Crucially, implicit self-control

enhanced connectivity within the two cognitive control brain networks in the theta frequency band. Specifically, for the frontoparietal network, increased connectivity from the dorsolateral PFC to the intraparietal cortex was observed. For the cingulo-opercular network, increased connectivity from dorsal anterior cingulate cortex to the left anterior insula/frontal operculum and from the right anterior insula/frontal operculum to the dorsal anterior cingulate cortex was observed. These effects were accompanied by a decrease in prestimulus alpha power in the right primary visual cortex, suggesting adjustment of attentional and perceptual processes in preparation for the upcoming affective stimulation. Together, our results indicate that self-control enhances cognitive control that is necessary for setting, maintaining, and monitoring the achievement of self-control behavior, as well as regulation of attentional and emotional processes. ■

INTRODUCTION

Self-control is a core aspect of adaptive human behavior. It can be broadly defined as a set of mental processes that allow the control of unwanted thoughts, emotions, and behavior (Inzlicht, Schmeichel, & Macrae, 2014). Self-control enables the attainment of personal goals by overriding prepotent responses (impulses or urges) or automatic action tendencies (to avoid threats and approach rewards). Previous studies highlighted the crucial role of cognitive control for self-control (Hofmann, Schmeichel, & Baddeley, 2012). Cognitive control refers to top-down processes including inhibition and interference control, working memory, and cognitive flexibility (Diamond, 2013). By flexible adjustments of processes like attention and memory, cognitive control enables goal formation, planning, carrying-out goal-directed plans, and monitoring the state of goal achievement (Hofmann et al., 2012). To achieve self-control, people need also to regulate unwanted (positive and negative) emotional experiences. For instance, if one's long-term goal is to save money (e.g., to buy a house), it would be adaptive to

downregulate positive emotions one obtains from indulging in short-term pleasures, such as dining out or buying superfluous gadgets, while planning and executing actions toward increase of incomes. It would also be adaptive to downregulate negative emotions of boredom or reluctance to work extra hours. Indeed, an influential line of research has demonstrated that people (are motivated to) spontaneously down- or up-regulate their emotions to promote desired behavior (see Tamir, 2016 for a review).

Recent research shows that it is possible to induce implicit pursuit of self-control that results in the reduction of emotional reactivity to affective contents. In a study by Wyczesany, Adamczyk, Ligeza, Bereś, and Marchewka (2021), participants were primed with reappraisal (e.g., “Changing perspective helps solve problems”) or more general self-control-related sentences (e.g., “The woman has accumulated a large amount of savings”) before passively viewing unpleasant or neutral pictures. Both reappraisal and self-control sentences were interleaved with emotionally neutral sentences (e.g., “She packed very comfortable shoes”) to conceal the self-regulatory nature of the task. All sentences were presented in a form of a sentence unscrambling task (i.e., a word puzzle) that participants had to solve (cf. Mauss, Cook, & Gross, 2007).

¹Radboud University, Nijmegen, The Netherlands, ²Jagiellonian University, Kraków, Poland

Compared with the control condition, in which only emotionally neutral sentences were presented, implicit induction of reappraisal and self-control decreased activity in visual and sensory cortices as well as amygdala in response to unpleasant pictures, indicating widespread emotion downregulation effects (Schaefer et al., 2002). Moreover, increased activity of the dorsolateral prefrontal cortex (DLPFC), a brain region implicated in domain-general cognitive control (MacDonald, Cohen, Stenger, & Carter, 2000), including cognitive control of emotion (McRae et al., 2010; Ochsner, Bunge, Gross, & Gabrieli, 2002), was observed. Importantly, unlike explicitly pursued self-control, these effects were observed without participants being aware of the self-regulatory nature of the task (which was confirmed using the funneled debriefing procedure; for details, see Wyczesany et al., 2021).

The above results suggest that such spontaneous or implicit emotion regulation (ER) can be considered a manifestation of self-control and that successful attainment of self-control (and ER) depends on the cognitive control (Pruessner, Barnow, Holt, Joormann, & Schulze, 2020). To lend further support for the above claim, in the present study, we aimed to verify whether implicit pursuit of self-control would enhance activity in cognitive control brain networks implicated in the explicit pursuit of self-control and the execution of cognitive control tasks. To address this question, we used the implicit self-control paradigm by Wyczesany and colleagues (2021) and recorded EEG signals from healthy participants. On the basis of previous studies (Wyczesany et al., 2021; Yuan, Ding, Liu, & Yang, 2015; Mauss et al., 2007), we expected that implicit self-control would result in the spontaneous attenuation of emotional responses to passively watched negative pictures content (i.e., implicit ER) and these regulatory effects would be reflected in decreased amplitudes of the late positive potential (LPP), a late-latency ERP that is a well-established index of ER effectiveness (Hajcak & Foti, 2020). We also measured the effects on subjective emotion experience (unpleasantness and arousal). However, as some studies observed modulation of subjective emotion experience by implicit ER (Zhang et al., 2023; Chen, Yu, Yang, & Yuan, 2020; Mauss et al., 2007), whereas others did not (Wyczesany et al., 2021; Yuan et al., 2015), we did not have a strong expectation whether our implicit self-control task would result in the downregulation of subjective unpleasantness and arousal.

Crucially, to test whether implicit self-control would enhance cognitive control, we measured EEG effective connectivity within two major brain networks implicated in sustained control over goal-directed behavior, that is, the frontoparietal and the cingulo-opercular networks (Power et al., 2011). The former includes the DLPFC and intraparietal cortex (intraparietal sulcus [IPS]) and is responsible for instantiating and flexibly coordinating cognitive control as well as modulating the activity of other brain networks (Marek & Dosenbach, 2018). The latter consists of the dorsal anterior cingulate (dACC) and

anterior insula/frontal operculum (aI/fo) areas, and monitors ongoing mental processing, signaling the need for increased attentional control upon detection of inadequate cognitive focus (Clayton, Yeung, & Cohen Kadosh, 2015). For the frontoparietal network, we hypothesized an increase in information from the dorsolateral to intraparietal regions and from the intraparietal to visual cortex, reflecting initializing and enforcing the top-down cognitive control, respectively (Sarter, Givens, & Bruno, 2001). Within-network connectivity was expected to increase in theta frequency band (Oehrn et al., 2014). An increase in information flow from the frontoparietal network toward the visual cortex was expected in beta frequency bands (Spadone, Wyczesany, Della Penna, Corbetta, & Capotosto, 2021; Ligeza & Wyczesany, 2017). Similarly, increased connectivity in theta band was expected between dACC and aI/fo in the cingulo-opercular network, reflecting the need for intensified attentional control (Cavanagh & Frank, 2014; Dosenbach et al., 2006). Finally, we also expected a decrease in prestimulus visual alpha power, a marker of anticipatory attention (Klimesch, 2012), which would reflect an active maintenance of the self-regulatory goal.

METHODS

Participants

Power analysis with PANGEA (Westfall, 2016)—a software for the estimation of power for linear mixed-models designs—indicated that 33 participants would allow to detect the two-level fixed effect based on an alpha level of .05, power of 0.80, and a small-to-medium effect size of $d = 0.4$. We chose to oversample in case of participant dropouts, EEG data collection failure, or excessive EEG artifacts. Thus, 36 adult women (mean age = 23.7 ± 2.3 years) were recruited to participate in the study in exchange for monetary compensation or course credits. Only female participants were included to control for gender differences in emotional picture processing (Filkowski, Olsen, Duda, Wanger, & Sabatinelli, 2017). All were right-handed, had normal or corrected-to-normal vision, and none reported a history of neurological or psychiatric disorders. In accordance with the Declaration of Helsinki, all procedures were carried out with the adequate understanding and written consent of the participants. The investigation was approved by the institutional ethics committee.

Stimuli

Sixty negative (M arousal = 5.9; SD arousal = 0.8; M valence = 2.1, SD valence = 0.5) and 60 neutral pictures from the International Affective Picture System (IAPS; Bradley, Hamby, Löw, & Lang, 2007) were used¹ (M arousal = 3.3 SD arousal = 0.6; M valence = 5.1, SD valence = 0.5; according to normative IAPS ratings).

Negative pictures were more unpleasant, $t(118) = 32.643$, $p < .0001$, $d = 5.96$, 95% confidence interval [CI] [5.12, 6.80], and arousing than neutral pictures, $t(118) = -20.88$, $p < .0001$, $d = -3.81$, 95% CI [-4.41, -3.21]. Negative pictures displayed violent scenes, sad people, animal mutilations, surgical procedures, and accidents. Neutral pictures displayed people engaged in everyday activities, neutral animals, household objects, and neutral landscapes. We attempted to match unpleasant and neutral pictures in terms of both color content and complexity (e.g., number of faces, number of body parts). Two sets of valence-, arousal- and content-matched unpleasant pictures were randomly allocated to the regulation condition (REG) and no-regulation condition (NREG) conditions. Two sets of valence-, arousal-, and content-matched neutral pictures were randomly allocated to the NREG and NREG2 conditions. The pictures were presented full screen at a viewing distance of approximately 60 cm and 50° of horizontal visual angle. The task was administered on a 61-cm LED monitor, using PsychoPy software (Peirce et al., 2019) to control the presentation and timing of the procedure.

Procedure

We used a validated implicit self-control goal induction procedure from Wyczesany and colleagues (2021; see Figure 1 for details). In contrast to the previous procedure, in the present study, we used two control conditions

NREG and NREG2, to check if picture-content-irrelevant (NREG) versus picture-content-relevant (NREG2) sentences could have influenced basic perceptual processing (i.e., by manipulating attention away vs. toward the picture, respectively). Example of the neutral sentences used: NREG: “He wrote a long letter”; NREG2: “The people presented [in the picture] are middle-aged.” In total, there were four conditions: NREG-NEU (in which picture-content-irrelevant neutral [NREG] sentences preceded presentation of neutral [NEU] pictures); NREG-NEU-2 (in which picture-content-relevant neutral [NREG2] sentences preceded presentation of NEU pictures), NREG-NEG (in which picture-content-irrelevant neutral [NREG] sentences preceded the presentation of negative [NEG] pictures), and REG-NEG (in which self-control-related and emotion-regulation goal-inducing [REG] sentences were mixed with picture-content-irrelevant neutral [NREG] sentences before the presentation of NEG pictures). For the full list of the sentences used, see Wyczesany et al., 2021, supplementary materials).

We created only one implicit ER condition in which REG sentences were mixed with NREG sentences (and not NREG2 sentences) not to manipulate the attentional deployment within one condition. Specifically, focusing attention on the neutral (vs. emotional) aspects of pictures has been shown to downregulate emotion responding and enhance activity within frontoparietal cognitive control networks (Ferri, Schmidt, Hajcak, & Canli, 2013; Dunning

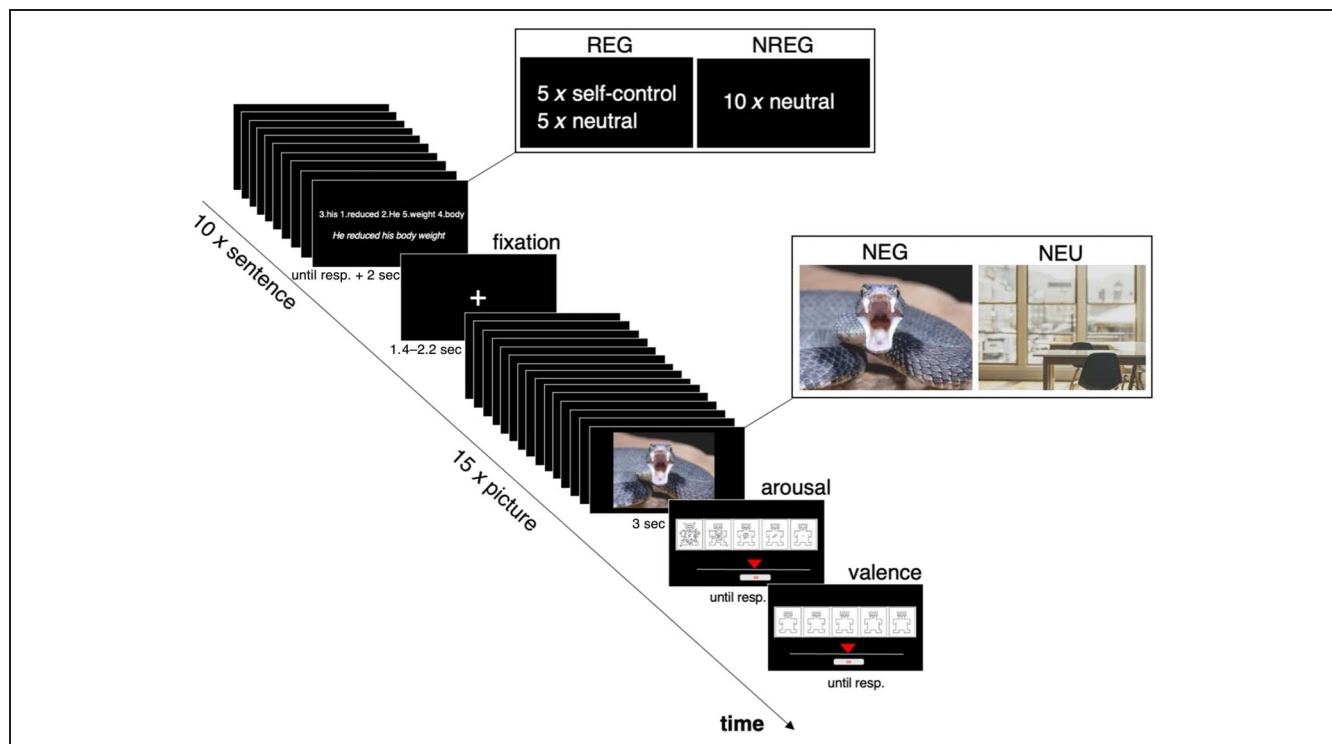


Figure 1. Experimental procedure. A sample (REG-NEG) block. In each block, participants unscrambled 10 sentences of either neutral (NREG) or neutral and self-control-related content (REG). Each unscrambled sentence was presented for 2 sec after unscrambling. Then, participants passively viewed 15 pictures of NEG or NEU valence. Each picture was presented for 3 sec and was preceded by a fixation cross (1.4–2.2 sec). At the end of each block, participants rated experienced arousal and unpleasantness (until response) on the Self-Assessment Manikin Scale. The procedure consisted of eight blocks in total (2 × REG-NEG, 2 × NREG-NEG, 2 × NREG-NEU, 2 × NREG-NEU2), presented pseudorandomly.

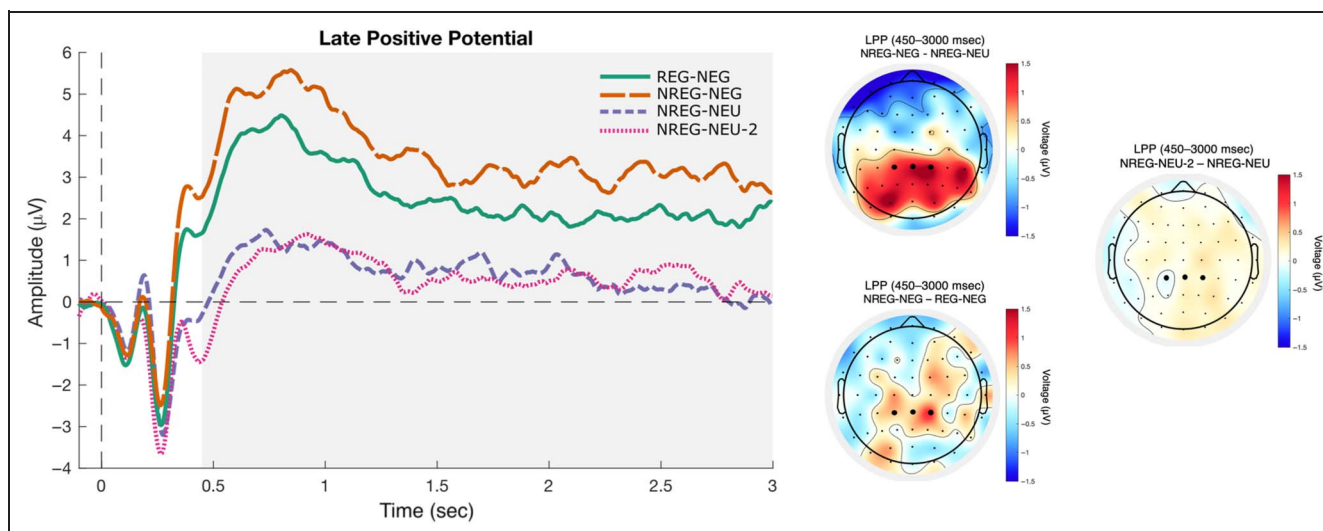


Figure 2. ERP results. Grand average waveforms for the LPP (left panel) and topographical maps indicating voltage differences between relevant conditions and electrodes from which the LPP was measured (right panel). The x axis runs from the beginning of the baseline (100 msec before picture onset) to the end of the picture presentation (3000 msec; LPP). Time 0 on the x axis marks picture onset (vertical dashed line). Shaded gray areas indicate the time window submitted to statistical analysis. For visualization, waveforms were smoothed with a moving average filter of a sliding window of length 20.

& Hajcak, 2009). Thus, with an implicit ER condition in which half of all sentences would direct attention toward neutral aspects of the pictures (e.g., people's age; NREG2), it would be impossible to disentangle whether observed differences were because of manipulation of attention deployment (by NREG sentences), ER goal-inducing nature of the REG sentences, or some interaction of these two processes.

EEG Recording, Preprocessing, and Analysis

The EEG signal was recorded using a BiosemiTwo device and a set of 64 cap electrodes, supplemented by two mastoid and four oculomotor (EOG) electrodes. EEG data were preprocessed using the Atlantis toolbox (<https://atlantis.psychologia.uj.edu.pl>), a custom software partly based on FieldTrip routines (Oostenveld, Fries, Maris, & Schoffelen, 2011).

ERP

For the ERP preprocessing, the following steps were applied: reference to the linked mastoids, 0.2-Hz high-pass and 47-Hz low-pass filtering (windowed sinc linear phase finite impulse response filters (order: HP 8448; LP 282), bad channel screening using variance extreme values; eye-movement correction with the recursive least square method (Gomez, 2007); segmentation relative to stimulus onset in the -0.1 - to 3-sec window; baseline correction using the prestimulus period; trial-based artifact rejection (or interpolation of bad channels if single electrode was affected) with the following parameters: excess variance ($5 \times$ interquartile range (IQR) threshold), range artifacts (150 μ V threshold), or muscle signal

contamination (detected by spectral power value for frequencies > 35 Hz). If less than 12 trials per condition (which is required to reliably measure the effects of ER on the LPP; Moran, Jendrusina, & Moser, 2013), the respective participant would have been excluded from the analysis including this condition; however, this was never necessary. The average number of retained trials was 27.5 per condition (range: 14–30) and did not differ significantly between conditions, $p > .97$. The LPP magnitudes were quantified as the average values within the 450–3000 msec and were measured from electrodes CP1, CPz, and CP2 (cf. Thiruchselvam, Blechert, Sheppes, Rydstrom, & Gross, 2011). The start of the LPP was determined by inspecting collapsed localizers (i.e., the grand average waveform collapsed across all experimental conditions for the selected electrode cluster; Luck & Gaspelin, 2017) to exclude the P3 from the LPP time-window during the initial implementation phase. Specifically, as a starting point for the LPP time-window, we took the local minimum after the P3-peak and before the LPP-peak (cf. Adamczyk, Wyczesany, Roelofs, & van Peer, 2023). To check if the selected electrode cluster showed enhanced activity in response to negative versus neutral stimuli (which could thus be downregulated), we also inspected the topographical map showing voltage differences between NREG-NEG minus NREG-NEU conditions (see Figure 2).

Connectivity

The connectivity preprocessing was based on the approach proposed in Mantini and colleagues (2011) and further extended in Spadone and colleagues (2021). The signal was filtered in a range of 2–47 Hz with windowed

sinc linear phase finite impulse response filters (high-pass filter order: 1264; low-pass filter order 282) and then segmented using a window of -1 to 3 sec relative to stimuli onset. Bad channels were detected using IQR-based extreme outliers rejection algorithm (threshold for channel variance set to $Q1/Q3 \pm 5$ IQR), calculated from EOG-corrected signals after the recursive least square method (Gomez-Herrero et al., 2006). Surviving original channels (without EOG correction) were rereferenced to the average of all channels. Trial-based artifact rejection consisted of extreme outliers removal based on variance (threshold set to $Q1/Q3 \pm 3$ IQR), maximum trial voltage difference ($< 300 \mu\text{V}$), and muscle artifact identification (based on elevated spectral power in a 35- to 47-Hz frequency). Remaining trials were decomposed with fastICA with deflation and pow^3 nonlinearity, and resulting components were classified using a previously trained model (with topography, spectral power, pre/post stimulus variance, correlation with EOG signals) into brain and non-brain independent components (ICs). The brain ICs were localized using their weight matrices with the minimum norm estimation method (Hämäläinen & Ilmoniemi, 1994) based on Montreal Neurological Institute standard templates (5-mm regular grid) and the three-layer Boundary Element Method (“bemcp”) volume conductor model (Fuchs, Kastner, Wagner, Hawes, & Ebersole, 2002). Locations of the ROIs were selected based on our hypotheses and previous literature (Spadone et al., 2021; Lacadie, Fulbright, Rajeevan, Constable, & Papademetris, 2008; Dosenbach et al., 2006; Papademetris et al., 2006; MacDonald et al., 2000): L/R primary visual cortex (V1; $-11 -81 7 / 11-78 9$); L/R intraparietal sulci (IPS; $-32 -48 44 / 32-52 50$); dACC ($-1 -10 46$); L/R anterior insula / frontal operculum (a/fo; $-35 14 5 / 36 16 4$); L/R DLPFC: ($-43 18 29 / 43 18 29$) were reconstructed as a sum of IC signals in the respective (closest) source dipole obtained as a product of particular IC time course and respective weight components separately for all spatial directions. The scalar value of the ROI signal was calculated by taking the first principal component derived from the three spatial components. To control for spurious correlation between estimated source time-courses, leakage correction was applied using a symmetric multivariate orthogonalization procedure (Colclough, Brookes, Smith, & Woolrich, 2015). Finally, connectivity between the ROIs were estimated for either theta (3–7 Hz) or beta (15–30 Hz) frequency bands using nonnormalized directed transfer function (Kaminski & Blinowska, 1991), a multivariate method based on Granger causality assumptions.

Spectral Power

The signal for the primary visual cortex was reconstructed as described in the Connectivity section above. One-second prestimulus intervals were subject to Welch method spectral estimation with 10% Hamming windowing. Resulting spectral values for the alpha window of 8–13 Hz were log-

transformed to obtain normal distribution (Wyczesany, Kaiser, & Coenen, 2010).

Statistical Analysis

Linear Mixed-effects Models

The data were analyzed in R, Version 4.2.2 (R Core Team, 2021) with a linear mixed-effects model (LMM) approach, using the lme4 package, Version 1.1.31 (Bates, Mächler, Bolker, & Walker, 2015). Extreme outliers were removed using the criterion $Q1/Q3 \pm 3$ IQR. Separate models were estimated for all outcome measures, that is, connectivity between ROIs, prestimulus alpha power, and LPP components and valence and arousal ratings. First, we performed manipulation checks for ERPs and subjective ratings. Specifically, to confirm that negative versus neutral pictures induced more negative emotions (valence and arousal) and enhanced sustained motivated (LPP) attention processing, we compared NREG-NEG versus NREG-NEU conditions (Manipulation Check 1 [MC1]). Second, to rule out the possibility that attention-disengaging nature of the sentences used in the sentence unscrambling task changed attention processing (regardless of the regulatory or neutral content of the sentences), we compared two control conditions: NREG-NEU versus NREG-NEU2 (Manipulation Check 2 [MC2]). Finally, and most importantly, to examine if implicit induction of self-control downregulated motivated attention (LPP) and subjective emotional responses (arousal, unpleasantness) to negative pictures, and increased connectivity within hypothesized brain networks, we compared REG-NEG versus NREG-NEG conditions.

All categorical predictors were coded using sum-to-zero contrasts. The following contrasts were used: MC1: NREG-NEG = 1, NREG-NEU = -1 ; MC2: NREG-NEU = 1, NREG-NEU2 = -1 ; ER: NREG-NEG = 1, REG-NEG = -1 . The repeated-measure nature of the data was modeled by including per-participant random adjustment to the fixed intercept (“random intercept”). The models were fitted using restricted maximum likelihood estimation. p Values were determined using conditional Type III F tests with Kenward–Roger correction of degrees-of-freedom (dfs), as implemented in the *Anova* function from the package Car (Fox & Weisberg, 2019), which calls the *KRmodcomp* function of the package pbkrtest (Halekoh & Højsgaard, 2014). CIs for parameter estimates were determined using parametric bootstrapping (1000 simulations) as implemented in lme4’s *bootMer* function and deriving 95% CIs (95% CI, type = “percentile”) using the function *boot.ci* of the package boot (Canty & Ripley, 2021). Cohen’s d standardized effect sizes were calculated using the function *lme.dscore* from the package EMAtools, Version 0.1.4 (Kleiman, 2021). Multiple comparison correction (false discovery rate [FDR]) was applied using the function *p.adjust* from the package stats, Version 4.2.2 (R Core Team, 2021). p Values were corrected in

Table 1. Manipulation Checks: Results for Subjective Ratings and ERPs

<i>Pairwise Comparison</i>	<i>Measure</i>	<i>B</i>	<i>95% CIs</i>	<i>SE</i>	<i>dfs</i>	<i>F</i>	<i>p</i>	<i>d</i>	<i>BF₁₀</i>
NREG-NEG vs. NREG-NEU (Manipulation Check 1)	Arousal	-0.78	-0.98, -0.59	0.10	1, 92.6	62.9	< .0001***	-1.65	> 100
	Valence	0.87	0.71, 1.04	0.08	1, 101	105.9	< .0001***	2.04	> 100
	LPP	1.44	0.87, 1.99	0.30	1, 35	23.0	< .0001***	1.62	> 100
NREG-NEU vs. NREG-NEU-2 (Manipulation Check 2)	Arousal	0.05	-0.06, 0.17	0.06	1, 91.2	0.84	.36	0.19	0.28
	Valence	0.01	-0.12, 0.13	0.07	1, 101	0.01	.91	0.02	0.29
	LPP	-0.04	-0.63, 0.54	0.30	1, 35	0.02	.89	-0.05	0.25

BF₁₀: Bayes Factor in favor of H1. **Bolded** font indicates statistically significant results.

*** $p < .001$.

the spectral analysis for laterality, and in connectivity analyses for directionality and laterality of effects.

Bayes Factor

Following recent recommendations (Keyesers, Gazzola, & Wagenmakers, 2020), we complemented our frequentist LMM analysis with a Bayes Factor analysis. We used a Jeffreys–Zellner–Siow prior, that is, a folded Cauchy distribution centered around $\delta = 0$ with the scaling factor for fixed effects $r = .5$. We compared the full model comprising the fixed effect of interest (H1) against the null (intercept-only) model (H0). All models included “participant” as a random grouping factor. To assign verbal labels to the strength of evidence, we followed the taxonomy suggested by Jeffreys (1961) in Wagenmakers and colleagues (2018). Data analyses were performed in R (R Core Team, 2021), using the function *lmBF* of the BayesFactor package, Version 0.9.12.4.4 (Wagenmakers et al., 2018).

RESULTS

Results for the manipulation checks (subjective ratings and ERPs) are reported in Table 1. Results for the effects of implicit self-control induction on emotional reactivity

(subjective ratings, ERPs, prestimulus alpha power) and neural connectivity (within theta and beta frequency bands) are reported in Table 2 and Table 3, respectively. Below, we report *F* statistic, *p* values, Cohen’s *d*, and *BF₁₀* for all manipulation checks, ER effects, and all significant neural connectivity effects.

Subjective Ratings

Because of a technical problem, arousal ratings collected for the last block in the procedure were lost for some participants. However, as the LMM method can deal with missing data, these participants were not excluded from the analyses.

As expected, negative pictures elicited stronger unpleasantness, $F(1, 101) = 105.9, p < .0001, d = 2.04, BF_{10} > 100$, and arousal, $F(1, 92.6) = 62.9, p < .0001, d = -1.65, BF_{10} > 100$, than neutral pictures in the NREG condition. NREG conditions did not differ between each other, which indicates that disengaging (NREG-NEU) or engaging (NREG-NEU2) content of the sentences did not affect unpleasantness, $F(1, 101) = 0.01, p = .91, d = 0.02, BF_{10} = 0.29$, and arousal, $F(1, 91.2) = 0.68, p = .41, d = 0.31, BF_{10} = 0.34$. In line with our previous study (Wyczesany et al., 2021), implicit self-control (REG condition) did not influence valence, $F(1, 101) = 3.0, p = .086, d =$

Table 2. Results for Subjective Ratings, ERPs, and Prestimulus Alpha Power

<i>Pairwise Comparison</i>	<i>Measure</i>	<i>B</i>	<i>95% CIs</i>	<i>SE</i>	<i>dfs</i>	<i>F</i>	<i>p</i>	<i>d</i>	<i>BF₁₀</i>
REG-NEG vs. NREG-NEG (ER)	Arousal	-0.02	-0.18, 0.13	0.08	1, 94.2	0.07	.79	-0.06	0.19
	Valence	-0.13	-0.27, 0.03	0.08	1, 101	3.0	.086 [†]	-0.34	0.35
	LPP	0.51	0.12, 0.93	0.20	1, 35	6.16	.018*	0.84	2.75
	α power (right V1)	-0.02	-0.04, -0.00	0.008	1, 35	5.57	.048*	-0.80	2.20
	α power (left V1)	-0.008	-0.03, 0.01	0.008	1, 35	0.52	.47	-0.24	0.30

Pairwise comparison between implicit self-control (REG-NEG) and no-regulation (NREG-NEG) conditions. FDR-corrected *p* values for alpha power. V1 = primary visual cortex; BF₁₀ = Bayes Factor in favor of H1. **Bolded** font indicates statistically significant results.

* $p < .05$.

† $p < .10$.

Table 3. Connectivity Results

<i>Brain Network</i>	<i>ROI Connectivity</i>	<i>b</i>	<i>95% CIs</i>	<i>SE</i>	<i>dfs</i>	<i>F</i>	<i>p_{uncorr.}</i>	<i>p_{FDR-corr.}</i>	<i>d</i>	<i>BF₁₀</i>
Frontoparietal (theta)	left DLPFC → left IPS	0.01	−0.01, 0.04	0.01	1, 34	1.18	.28	.30	0.37	0.40
	left DLPFC → right IPS	0.02	0.01, 0.03	0.006	1, 32.5	11.02	.002**	.009**	1.20	16.3
	right DLPFC → left IPS	0.02	−0.01, 0.02	0.009	1, 31.4	6.54	.016*	.031*	1.0	3.87
	right DLPFC → right IPS	−0.006	−0.02, 0.00	0.005	1, 32.5	1.11	.30	.30	−0.37	2.43
Frontoparietal with visual (beta)	left IPS → left V1	0.00	−0.01, 0.01	0.005	1, 34.3	0.00	.99	.99	0.0	0.24
	left IPS → right V1	0.003	−0.00, 0.0	0.003	1, 33	1.00	.32	.65	0.35	0.38
	right IPS → left V1	−0.008	−0.02, 0.0	0.007	1, 32.2	1.36	.25	.65	−0.42	0.42
	right IPS → right V1	0.002	−0.01, 0.01	0.004	1, 29.7	0.23	.64	.85	0.19	0.29
Cingulo-opercular (theta)	dACC → left aI/fO	0.43	0.19, 0.69	0.13	1, 31.2	11.55	.002**	.007**	1.22	21.8
	dACC → right aI/fO	−0.05	−0.30, 0.17	0.12	1, 33.5	0.20	.66	.78	−0.16	0.26
	left aI/fO → dACC	−0.01	−0.11, 0.06	0.04	1, 33.5	0.08	.78	.78	−0.10	0.26
	right aI/fO → dACC	0.25	−0.03, 0.47	0.13	1, 34.4	4.10	.051[†]	.10	0.70	1.29

Pairwise comparison between implicit induction of self-control (REG-NEG) and no-regulation (NREG-NEG) conditions. aI = anterior insula; fO = frontal operculum; BF₁₀ = Bayes Factor in favor of H1. **Bolded** font indicates statistically significant results.

* $p < .05$.

** $p < .01$.

[†] $p < .10$.

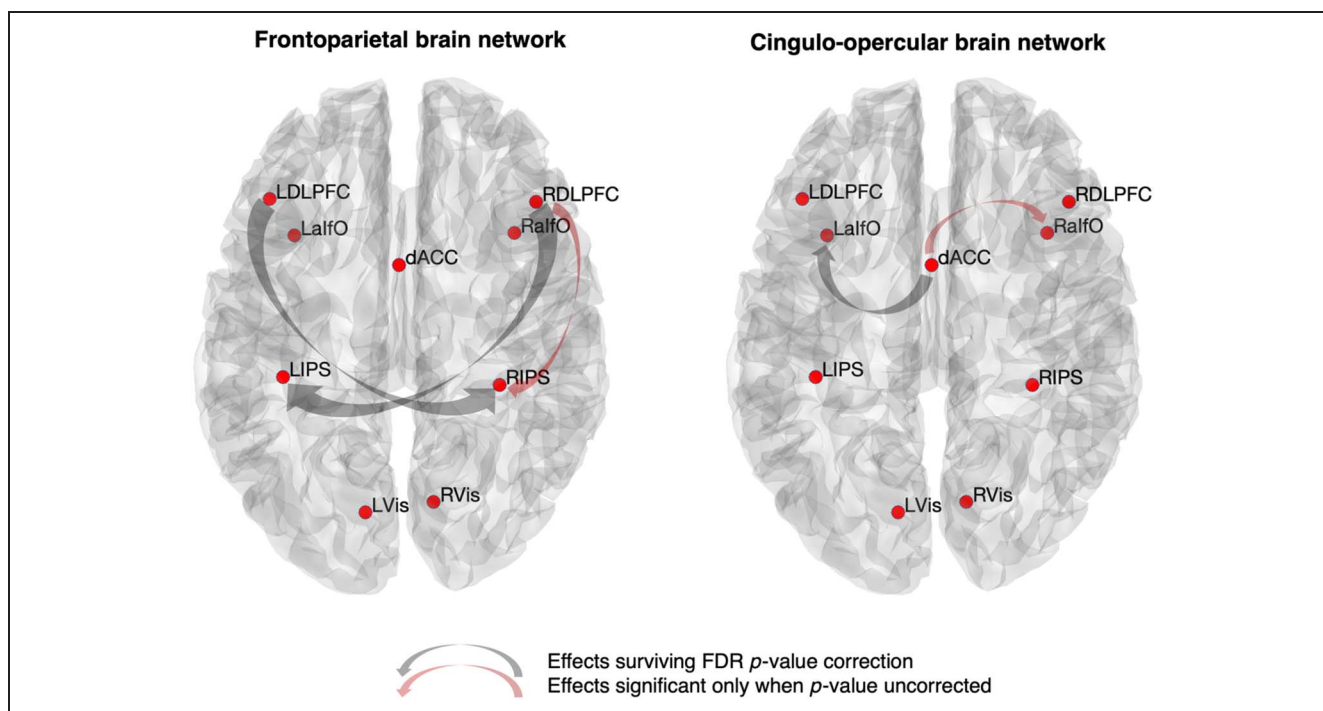


Figure 3. Connectivity results. Arrows indicate significant directional increase in information flow (i.e., effective connectivity effects) between preselected ROIs in theta (3–7 Hz) frequency band in the implicit self-control (REG-NEG) compared with the no-regulation (NREG-NEG) condition. Left: Effects for the frontoparietal network (L/RDLPFC = left/right dorsolateral prefrontal cortex; L/RIPS = left/right intraparietal sulcus). Right: Effects for the cingulo-opercular network (L/RalfO = left/right anterior insula/frontal operculum).

-0.34 , $BF_{10} = 0.35$, and arousal ratings, $F(1, 94.2) = 0.07$, $p = .79$, $d = -0.06$, $BF_{10} = 0.19$, compared with the NREG condition.

ERPs

As expected, negative pictures evoked enhanced LPP amplitudes compared with neutral pictures in the NREG-NEG versus NREG-NEU condition (Manipulation Check 1), $F(1, 35) = 23.0$, $p < .0001$, $d = 1.62$, $BF_{10} > 100$. NREG conditions did not differ between each other, which indicates that disengaging (NREG-NEU) or engaging (NREG-NEU2) content of the sentences did not modulate late sustained motivated (LPP) attention processing (Manipulation Check 2), $F(1, 35) = 0.02$, $p = .89$, $d = -0.05$, $BF_{10} = 0.25$. Finally, and most importantly, implicit induction of self-control (REG-NEG) reduced the LPP amplitude in response to negative pictures compared with the NREG-NEG condition, $F(1, 35) = 6.16$, $p = .018$, $d = 0.8$, $BF_{10} = 2.75$.

Connectivity

Within the frontoparietal network, there was increased connectivity in the theta frequency band observed from the left DLPFC to the right IPS, $F(1, 32.5) = 11.02$, $p_{FDR-corr.} = .009$, $d = 1.20$, $BF_{10} = 16.3$, and from the right DLPFC to the left IPS, $F(1, 31.4) = 6.54$, $p_{FDR-corr.} =$

$.031$, $d = 1.0$, $BF_{10} = 3.87$. Within the cingulo-opercular network, there was increased connectivity in the theta frequency band observed from the dACC to the left aI/fO, $F(1, 31.2) = 11.55$, $p_{FDR-corr.} = .007$, $d = 1.22$, $BF_{10} = 21.8$. The effect from the right aI/fO to dACC was marginally significant ($p_{uncorr.} = 0.51$) and did not survive FDR-correction, $F(1, 34.4) = 4.10$, $p_{FDR-corr.} = .10$, $d = 0.70$, $BF_{10} = 1.29$ (Figure 3).

Spectral Power

After implicit induction of self-control goal (REG-NEG), prestimulus alpha power in the right primary visual cortex was significantly lower compared with the NREG-NEG condition, $F(1, 35) = 5.57$, $p_{FDR-corr.} = .048$, $d = -0.80$, $BF_{10} = 2.20$.

DISCUSSION

The present study investigated whether implicitly pursued self-control engages cognitive control and whether it subsequently attenuates emotional responses to affective content. In line with previous studies, implicit self-control reduced LPP responses to negative pictures, indicating successful emotion downregulation compared with no-regulation conditions. Importantly, in line with our main hypothesis, implicit self-control enhanced connectivity within the two cognitive control brain networks: the

frontoparietal and the cingulo-opercular, in theta frequency band. Specifically, for the frontoparietal network, increased connectivity from the DLPFC to IPS was observed. For the cingulo-opercular network, increased connectivity from dorsal ACC to the left anterior insula and from the right anterior insula to the dorsal ACC was observed. These effects were accompanied by a decrease in prestimulus alpha power in the right primary visual cortex, suggesting adjustment of attentional and perceptual processes in preparation for the upcoming affective stimulation. Together, these findings indicate that self-control enhances cognitive control that is necessary for setting, maintaining, and monitoring the current state of achievement of self-control behavior, as well as regulation of attentional and emotional processes. Below, we discuss these results in detail and suggest potential implications and directions for future studies.

First, as a manipulation check, we verified the induction of negative emotions in the no-regulation (NREG) conditions. As expected, participants reported higher unpleasantness and arousal, and showed stronger (i.e., more positive) LPP responses to negative versus neutral pictures. Both frequentist and Bayesian statistics provided very strong support for these effects. As a second manipulation check, we verified whether picture irrelevant (NREG) versus relevant (NREG2) content of the sentences could have influenced basic perceptual processing of the pictures. Frequentist and Bayesian statistics provided converging evidence for the lack of differences in ERP amplitudes and subjective ratings between these two NREG conditions.

After these manipulation checks, we verified the efficacy of our experimental paradigm in reducing emotional reactivity. As expected, we observed a decrease in the LPP amplitudes in response to negative pictures in the implicit self-control regulation versus no-regulation condition. Bayes Factor analysis additionally provided moderately strong support for this effect. This finding is in line with our previous fMRI study, in which decreased activity of the amygdala and sensory cortices were observed (Wyczesany et al., 2021) and suggest that implicit self-control task modulated the late elaborative (LPP) attention processing. In addition, in line with our previous study, implicit self-control did not influence subjective emotion experience. However, as some studies suggested that implicit ER successfully downregulates subjective emotion experience (Zhang et al., 2023; Chen et al., 2020; Mauss et al., 2007), this null finding deserves an explanation.

First, our implicit self-control task might have exerted more subtle ER effects at subjective experience level than other implicit and explicit ER procedures. Specifically, in our previous study (Wyczesany et al., 2021), we confirmed—using a well-validated funneled debriefing procedure (Bargh & Chartrand, 2014)—that participants remained unaware of the ER goal in the implicit self-control group (in which the same task as in the present

study was used) but some participants become aware of the ER nature of the task in the implicit reappraisal group. As majority of studies on implicit ER used some form of an implicit reappraisal task (Zhang et al., 2023; Liu, Wang, & Li, 2018; Wang & Li, 2017), this potentially higher awareness of a regulatory goal might explain the divergent results regarding the impact of implicit ER on subjective emotion experience between our and other studies on implicit ER. Relatedly, although in the implicit reappraisal tasks the goal is to achieve ER, in our self-control task, ER is more instrumental as it serves to achieve a more general self-control goal (see Tamir, 2016, for distinction on instrumental and hedonic ER). This difference might also potentially explain why implicit ER processes (and their impact on subjective emotion experience) were less likely to reach the level of awareness in our task compared with other implicit ER tasks. Finally, the effects of implicit ER on subjective emotion experience might have been moderated by individual differences. For instance, implicit ER has been shown to exert stronger regulatory effects in those who do not habitually use explicit-controlled ER strategies such as reappraisal (Mauss et al., 2007) but weaker effects in individuals with high trait anxiety (Liu et al., 2018). Because in the present study we did not measure these individual characteristics, it would be important to account for these moderators in future studies.

Confirming the downregulation of emotional responses in the implicit self-control condition (i.e., the LPP amplitudes between REG and NREG conditions), we sought to investigate the neural sources of these effects. Results of our connectivity analyses showed the enhanced theta connectivity within the regions of frontoparietal and cingulo-opercular cognitive control networks. Specifically, for the frontoparietal network, the increase of information flow from the left DLPFC to the right IPS and from the right DLPFC to the left IPS were observed. For the cingulo-opercular network, we observed increased information flow from the dorsal ACC to the left aI/fo. Moreover, Bayesian statistics also suggested anecdotal evidence for the increased directed connectivity from the right aI/fo to the dorsal ACC. These findings are in line with the results of our previous fMRI study (Wyczesany et al., 2021), where increased activation of the bilateral DLPFC and anterior insula was observed after implicit induction of self-control.

The frontoparietal and cingulo-opercular networks are thought to support core cognitive functions engaged in sustained control of attention during visual attention tasks. Specifically, ACC is thought to monitor and trigger; whereas the DLPFC, to exert adaptive modification of ongoing processing by transmitting excitatory and inhibitory signals to lower-level sensorimotor cortices (Clayton et al., 2015). Indeed, in both fMRI (Marek & Dosenbach, 2018; Power et al., 2011) and EEG studies (Clayton et al., 2015; Cavanagh & Frank, 2014), increased hemodynamic activity/theta power in ACC and DLPFC has been observed in tasks requiring sustained monitoring and flexible

adjustment of attention and perceptual processes upon the detection of task-inappropriate performance or cognitive focus. Successful downregulation of emotional responses can also be viewed as a process of establishing and maintaining a (regulatory) goal, which is then accomplished by prolonged monitoring and control over attentional and perceptual processes (Ochsner & Gross, 2005). Although various ER strategies attain this control in different ways (for instance, by changing the meaning of emotional stimulus [cognitive reappraisal], reorienting attention to non-emotional parts of the stimulus [attentional distraction], or changing the cognitive focus from external to internal [cognitive distraction]), mechanisms that exert these top-down regulatory influences seem to be shared with the domain-general cognitive control. Indeed, accumulating evidence shows that neural networks engaged in implicit and explicit ER (Etkin, Büchel, & Gross, 2015; Ochsner, Silvers, & Buhle, 2012) significantly overlap with those involved in domain-general cognitive control tasks (Dosenbach et al., 2006; MacDonald et al., 2000). Given the observed pattern of findings in our study, we can thus conclude that implicit self-control recruits cognitive control mechanisms that are involved in the execution of explicit ER (Braunstein, Gross, & Ochsner, 2017) and cognitive control tasks (Marek & Dosenbach, 2018).

Given that cognitive control networks are known to exert modulatory influence on attentional processes and that such modulation is present during explicit ER procedures (Wyczesany et al., 2022; Wyczesany, Ligeza, & Grzybowski, 2015; Viviani, 2013), we also measured the prestimulus alpha power in primary visual cortices, which is a well-established marker of anticipatory attention (Klimesch, 2012). As expected, implicit induction of self-control decreased the alpha power compared with the no-regulation condition. However, this reduction was present only in the right but not the left primary visual cortex. Decreased prestimulus visual alpha power (or event-related alpha desynchronization) was shown to predict performance in object recognition and target detection paradigms (Mathewson et al., 2014) and has been suggested to reflect active maintenance of target information in an attentional buffer (Klimesch, 2012). Thus, in our study, we interpret decreased alpha power as a reflection of the active maintenance of an induced self-regulatory goal. Such goal maintenance could have guided attentional control (which shows the right-hemisphere lateralization; Spagna, Kim, Wu, & Fan, 2020), enabling the categorization of the emotional material as goal-irrelevant information. This could, in turn, facilitate the suppression of processing of (goal-irrelevant) negative stimuli contents, which was reflected in the decreased LPP amplitudes in response to negative picture content.

Notably, despite the modulation of the visual prestimulus alpha power, we failed to observe the hypothesized top-down regulatory effects, that is, increase in information flow, from the parietal cortex to the primary visual

cortices measured in the beta frequency band. Although previous studies suggested that parietal and visual cortices communicate in beta band oscillations (Spadone et al., 2021; Ligeza & Wyczesany, 2017), it is also plausible that these relatively long-range communication was supported by cross-frequency coupling (e.g., parietal beta; cf. Bramson, Jensen, Toni, & Roelofs, 2018) and visual alpha (cf. Wyczesany, Capotosto, Zappasodi, & Prete, 2018; see also Clayton et al., 2015, for an overview). Alternatively, the putatively reentrant regulatory effects originating in the frontoparietal network might have affected association rather than primary visual areas (Romeo et al., 2022). Resolving this issue would be important for establishing the mechanisms involved in the robust modulation of the sensorimotor cortices observed in our previous study (Wyczesany et al., 2021).

Some limitations of our study should be mentioned. First, we did not equalize the pictures with regard to low-level physical characteristics (such as contrast, luminance, and spatial frequencies; cf. Adamczyk et al., 2023). As these characteristics are known to influence early (P1, N1) and mid-latency (Early Posterior Negativity) components (Bradley et al., 2007; Schupp, Junghöfer, Weike, & Hamm, 2003), we were not able to reliably examine the effects of our implicit self-control task on early perceptual and automatic attention processing. As some studies suggested that implicit ER modulates early perceptual and attentional stages of stimuli processing (Liu et al., 2018; Wang & Li, 2017), it would be important for future studies to control the influence of these low-level physical features. Second, although we observed robust modulation of the LPP component that persisted throughout the picture presentation (i.e., 450–3000 msec)—which complements results of our previous study in which reduced neural activity in sensory cortices and the amygdala have been observed (Wyczesany et al., 2021)—it would be beneficial to include additional psychophysiological measures (e.g., heart-rate variability, skin conductance response, pupil size, or facial electromyography) to lend further support for the efficacy of our implicit self-control procedure in downregulating emotional responses and determine its impact on other components of emotional response. For instance, future studies could use electromyography to measure corrugator supercilia (“frown muscle”) activity, which has been shown to reflect subjective unpleasantness in response to emotional pictures and function independent of shifts in visual attention (Urry, 2010). This would allow to investigate the impact of implicit ER on expressive facial behavior and to disentangle the effects of implicit ER on attention and emotion. Using pupil size could also shed light into effortfulness (i.e., consumption of cognitive resources) of the implicit versus explicit ER (or REG vs. NREG conditions; Strauss, Ossenfort, & Whearty, 2016). It is important to note here that implicit ER has been suggested to consume less cognitive resources than explicit ER (Yuan et al., 2023; Zhang et al., 2023). Given the above, it is possible that uncovering

some of the potentially more subtle effects of our implicit self-control task (e.g., on subjective emotion experience or the connectivity between parietal and visual cortices) would require bigger sample size and/or controlling for potential moderating factors (such as previously mentioned individual differences in habitual use of reappraisal or trait anxiety).

To conclude, the present study shows that implicit self-control activates domain-general cognitive control systems that enable the maintenance, monitoring, and prolonged pursuit of self-regulatory behavior. These increases in cognitive control enable adjustment of the attentional and perceptual systems required for downregulation of emotional responses to (goal-irrelevant) negative stimulation in the service of pursued goals. Using implicit paradigms to study ER brings several important benefits compared with explicit ER paradigms. First, using implicit ER paradigms, which disguise the goal of the experiment, one can examine more natural (i.e., automatically initiated and executed) ER processes. In particular, implicit (automatic/spontaneous) ER processes that happen outside of one's awareness seem to be the default (and resource-effective; Yuan et al., 2023; Zhang et al., 2023) way in which people regulate their (low-intensity) emotional responses to distracting and potentially goal-interfering (external and internal) stimuli (e.g., an internal urge to check an email when waiting for an important decision or an emotional response to an external sound of an email prompt). Unless emotions are of relatively high intensity, they rarely enter our awareness and change our conscious goal priorities, for example, from focusing on driving to arrive on time for an important meeting to downregulating anger with a slow driver that impedes the achievement of this goal. Thus, examining implicit (and instrumental) ER processes might provide insights into this seemingly more prevalent way of regulating emotions in our everyday life. Second, our procedure is free from task load (i.e., participants are instructed to simply watch emotional pictures in both REG and NREG conditions)—which can incidentally *disrupt* (Adamczyk, Wyczesany, & van Peer, 2022) or, conversely, facilitate ER (Adamczyk, Ligeza, & Wyczesany, 2020; see de Voogd & Hermans, 2022; Van Dillen & Derks, 2012, for a review on the downregulatory impact of limiting working memory/attentional resources on emotion processing). Thus, our implicit self-control task could contribute to identifying ER-specific (and task-independent) neural activations. Finally, patients suffering from affective disorders seem to be capable of downregulating emotion responses to affective stimuli when instructed to do so (Liu & Thompson, 2017), but initial evidence suggests that what might be disrupted are implicit (i.e., spontaneously/automatically initiated) ER processes (Hoid, Pan, Wang, & Li, 2020; Liu et al., 2018; Ajaya, Peckham, & Johnson, 2016; Sheeran, Gollwitzer, & Bargh, 2013; Etkin, Prater, Hoedt, Menon, & Schatzberg, 2010). Thus, implicit paradigms could be useful for unraveling and potentially also

training the deficient ER skills (Yuan et al., 2023; Zhang et al., 2023).

Reprint requests should be sent to Agnieszka K. Adamczyk, Thomas van Aquinostraat 4, 6525 GD Nijmegen, NL, or via e-mail: agnieszka.adamczyk@ru.nl.

Data Availability Statement

All data and analysis code have been made publicly available at the Open Science Framework and can be accessed at <https://osf.io/2prf9/>.

Author Contributions

Agnieszka K. Adamczyk: Conceptualization; Data curation; Formal Analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing—Original draft. Mirosław Wyczesany: Conceptualization; Data curation; Formal Analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Writing—Original draft.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were $M(\text{an})/M = .407$, $W(\text{oman})/M = .32$, $M/W = .115$, and $W/W = .159$, the comparable proportions for the articles that these authorship teams cited were $M/M = .549$, $W/M = .257$, $M/W = .109$, and $W/W = .085$ (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

Note

1. IAPS pictures codes: neutral (1122, 2101, 2102, 2104, 2107, 2190, 2191, 2200, 2210, 2221, 2383, 2393, 2396, 2411, 2440, 2446, 2480, 2512, 2516, 2570, 2575, 2579, 2593, 2597, 2620, 2630, 2635, 2745.1, 5040, 5130, 5395, 5471, 5530, 5740, 7001, 7002, 7003, 7010, 7012, 7019, 7035, 7055, 7056, 7057, 7059,

7090, 7100, 7140, 7150, 7161, 7211, 7217, 7487, 7491, 7500, 7550, 7595, 7700, 7705, 7950); Negative (2141, 2691, 3016, 3103, 3168, 3530, 6212, 6840, 9042, 9253, 9423, 9425, 9490, 9600, 9908, 2683, 2695, 3051, 3140, 3185, 6021, 6571, 6831, 9050, 9220, 9410, 9414, 9433, 9435, 9611, 2205, 2710, 2718, 2900, 3225, 3301, 3350, 6311, 6313, 6825, 9250, 9520, 9530, 9921, 6570.1, 2095, 2456, 2717, 2750, 3181, 3220, 3230, 6010, 6312, 6360, 6520, 8485, 9412, 9421, 9903).

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