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Emotions under control? Better cognitive control is associated with reduced negative emotionality but increased negative emotional reactivity within individuals.

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ABSTRACT

Associations between impaired cognitive control and maladaptive emotion regulation have been extensively studied between individuals. However, it remains unclear if this relationship holds within individuals. In this study, we tested the assumption that momentary within-person fluctuation in cognitive control (working memory updating and response inhibition) is associated with emotional reactivity in everyday life. We conducted an experience sampling study (eight two-hourly prompts daily) where participants repeatedly performed short 2-back and Go/no-go tasks in daily life. We assessed negative and positive affective states, and unpleasantness of a recent event to capture emotional reactivity. We analyzed two overlapping samples: a Go/no-go and a 2-back dataset (N = 161/158). Our results showed that better momentary working memory updating was associated with decreased negative affect if the recent event was on average unpleasant for the given individual. However, better-than-average working memory updating in interaction with higher event-unpleasantness predicted higher negative affect levels (i.e., higher negative emotional reactivity). These findings may challenge the account of better cognitive control being universally related to adaptive emotion regulation. Although it is unlikely that emotional reactivity boosts working memory, future studies should establish the direction of causality.

1. Introduction

Cognitive control refers to the ability to regulate attention, thoughts, and behavior in order to achieve goals (Friedman & Miyake, 2017). In the context of emotion regulation, cognitive control plays a crucial role in modulating emotional responses and managing emotional experiences (Pruessner, Barnow, Holt, Joormann, & Schulze, 2020). Disturbances in cognitive control are associated with affective dysregulation (Morawetz, Bode, Baudewig, & Heekeren, 2017; Pruessner et al., 2020). Most prominently, impairments in working memory and response inhibition are correlated with maladaptive emotion regulation strategies, particularly rumination (Cohen, Mor, & Henik, 2015; Hasegawa et al., 2021; Hofmann, Schmeichel, & Baddeley, 2012; Joormann & Tanovic, 2015; McRae, Jacobs, Ray, John, & Gross, 2012; Whitmer & Gotlib, 2013).

However, maladaptive emotion regulation might be more specifically linked to the processing of negative content, not to general cognitive control impairment. For example, Cohen et al. (2015) designed a study in which, after performing a flanker task, neutral and negative emotion-eliciting pictures were shown to the participants. Their results showed that individuals who received flanker tasks requiring stronger resistance to distractor interference (i.e., higher rates of incongruent stimuli) before negative emotional stimuli reported lower rumination after the training. This implies that recruiting cognitive control can reduce interference with and promote inhibition of irrelevant emotional information.

Furthermore, others found that better working memory updating predicted greater efficiency of reappraisal in reducing negative emotions (Hendricks & Buchanan, 2016). The empirical findings of such positive associations between cognitive control and emotion regulation align

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well with clinical considerations in cognitive behavioral therapy, where the goal is to efficiently downregulate prepotent, maladaptive responses and thought patterns and replace them with more adaptive interpretations (Joormann & Quinn, 2014).

A sign of affective dysregulation is enhanced negative emotional reactivity (Thompson et al., 2012), a negative affective response to stressors (see Fig. S1 in Supplementary Materials) that manifests in the phenomenological, behavioral, and physiological domains (see Bylsma, Taylor-Clift, & Rottenberg, 2011). Enhanced emotional reactivity is predictive of various mental health problems such as psychosis (Myin-Germeys, van Os, Schwartz, Stone, & Delespaul, 2001), affective disorders (Myin-Germeys et al., 2003; Shapero et al., 2019; Thompson et al., 2012), and suicidality (Shapero et al., 2019). It is also associated with childhood traumas (Glaser, van Os, Portegijs, & Myin-Germeys, 2006), suggesting that emotional reactivity could be involved in etiological pathways leading to poor mental health (Copeland et al., 2018).

The relationship between cognitive control and emotionality might be also associated with how individuals tend to regulate their emotions. Pe, Raes, and Kuppens (2013) evaluated whether individual differences on a baseline n-back and a memory interference resolution task moderate the impact of emotion regulation on affective states in daily life. They found that enhanced trait-level working memory updating in combination with stronger momentary reappraisal was connected to reduced anger and anxiety. Furthermore, lower cognitive control combined with stronger momentary rumination predicted increased anger and anxiety (Pe et al., 2013).

It has also been suggested that improved working memory may have a causal effect on emotion regulation, since working memory training can improve reappraisal and decrease rumination in daily life (Hoorelbeke, Koster, Demeyer, Loeys, & Vanderhasselt, 2016, 2023). In addition, multiple studies established the efficiency of cognitive control training in enhancing emotion regulation (Joormann & Quinn, 2014; Schweizer, Grahn, Hampshire, Mobbs, & Dalgleish, 2013; Xiu, Wu, Chang, & Zhou, 2018).

However, one can find studies in the literature that contradict the latter arguments. In another study of Pe et al. (2015), they found that individuals with higher trait-level working memory performance showed a larger increase in negative emotions after viewing negative emotion-evoking films, compared to baseline levels of negative emotions. This means that higher working memory performance across individuals was associated with elevated negative emotional reactivity. The latter finding raises the suspicion that improved cognitive control might not always be beneficial for adaptive emotion regulation.

Making predictions at the level of individuals is hindered by the scarcity of within-individual studies and most previous studies did not examine within-individual fluctuation in cognitive control and affectivity simultaneously (see Hoorelbeke et al., 2023; Pe et al., 2013, 2015). This is problematic since inference based on cross-sectional designs may not generalize to individuals: performance on self-regulation tasks fluctuates within individuals (Enkavi et al., 2019), and within-person associations between affective functioning differ remarkably from one individual to another (Fisher, Medaglia, & Jeronimus, 2018). Nevertheless, despite the theoretical relevance of fluctuations in cognitive control for emotionality (Pruessner et al., 2020), these dynamic aspects have mostly been neglected in mental health research. Thus, modeling within-person changes and interactions between affective dysregulation and cognitive control is essential in advancing cognitive interventions that aim to boost mental health.

Preliminary studies in this direction looked at snacking behavior (Powell, McMinn, & Allan, 2017), problematic alcohol consumption (Jones, Tiplady, Houben, Nederkoorn, & Field, 2018), eating disorders (Smith et al., 2020) and positive affect (Brose, Lövdén, & Schmiedek, 2014). For example, within-individual deterioration in prepotent response inhibition predicted the consumption of unhealthy snacks in the next couple of hours (Powell et al., 2017). In addition, momentary negative affect had a stronger association with subsequent binge eating, if daily performance on inhibitory control was reduced, according to a study of individuals with eating disorders (Smith et al., 2020). Furthermore, better working memory performance was associated with increased positive affect within individuals on a daily basis (Brose et al., 2014). Together, these initial results imply that temporal fluctuations in cognitive control may relate to self-regulation and positive affect. Thus, such fluctuations might also affect the effectiveness of emotion regulation over time (Pruessner et al., 2020). However, this hypothesis remains to be tested.

The aim of the present study was to test the association of cognitive control and emotional reactivity within individuals in everyday life. Therefore, in this study, we investigated how dynamics of cognitive control moderate momentary emotional reactivity. According to the existing literature, disturbances in cognitive control are related to enhanced negative emotional reactivity across individuals, while better cognitive control positively predicts the adaptiveness of emotion regulation (Hendricks & Buchanan, 2016; Hoorelbeke et al., 2016; Joormann & Quinn, 2014; Schweizer et al., 2013; Xiu et al., 2018). Moreover, within-individual variation in cognitive control shows associations with maladaptive emotion regulation strategies, disrupted self-regulation, and positive affective states (Brose et al., 2014; Jones et al., 2018; Pe et al., 2013; Powell et al., 2017; Smith et al., 2020). However, according to other findings, increased cognitive control may be associated with more intense negative emotional reactivity (Pe et al., 2015). Here, we tested a specific hypothesis about the association of cognitive control with the intensity of distinct positive and negative affective responses to unpleasant events (i.e., emotional reactivity) within individuals. We expected that momentary response inhibition and working memory updating would negatively predict emotional reactivity: the better the individual's cognitive control performance compared to their typical level, the lower emotional reactivity they show.

2. Methods

2.1. Participants and screening

We recruited individuals from the general population through calls released in the press and posted on social media. They were first asked to undergo a cross-sectional baseline assessment; 221 participants completed this (N [female] = 163, mean [age] = 40.44 years, sd [age] = 14.24 years, min [age] = 18, max [age] = 78; see initial sample in Table 1). Of this initial pool, 209 individuals proceeded to the second, longitudinal phase of the study, which included two-hourly assessments involving experience sampling methods (ESM) and short cognitive tasks. Responses of the baseline assessment were screened; for details see 'Baseline participant screening' in the Supplementary Materials.

To avoid significant data loss and to increase statistical power, we analyzed performance on the Go/no-go and 2-back tasks using separate but almost completely identical datasets (156 participants were identical in the two samples, which makes up 96.9% of the Go/no-go and 98.7% of the 2-back dataset; for more details see Statistical Analysis).

The Go/no-go dataset comprised 161 individuals, who completed a total of 2494 Go/no-go tasks and ESM surveys (per capita: median = 10, obs. range = 1–68, theor. range = 1–224) and 2305 2-back tasks (per capita: median = 9.5, obs. range = 1–67, theor. range = 1–224). The 2-back dataset consisted of 158 individuals, who completed a total of 2641 2-back tasks and ESM surveys (per capita: median = 10.5, obs. range = 1–70, theor. range = 1–224), and 2305 Go/no-go tasks (per capita: median = 9.5, obs. range = 1–67, theor. range = 1–224). Demographic characteristics of the samples are reported in Table 1. Descriptive statistics of measures in the ESM phase can be found in Table S1 (see Supplementary Materials). We compared participants to evaluate any potential sampling bias introduced by the analysis of two separate (but overlapping) datasets; for details, see 'Dataset comparison' in Supplementary Materials and Table 1.

Table 1
Demographic characteristics of study samples.

	Initial sample	Participants excluded from analyses	Go/no-go sample	2-back sample	Comparison of 'Go/no-go' and 'Not included'	Comparison of '2-back' and 'Not included'
Size	221	41	161	158		
Age					$U = 2471$, $\boldsymbol{p} = \mathbf{0.013}^*$ $r = 0.175$	$U = 2422.5$, $\boldsymbol{p} = \mathbf{0.013}^*$ $r = 0.176$
Mean	40.44	35.59	41.74	41.78		
Median	38	35	41	40		
SD	14.24	12.7	14.5	14.54		
Range	18–78	18–65	18–78	19–78		
Sex					χ^2 (1) = 7.257, $\boldsymbol{p} = \mathbf{0.007}^{**}$$V = 0.190$	χ^2 (1) = 7.364, $\boldsymbol{p} = \mathbf{0.007}^{**}$$V = 0.192$
Female % (N)	73.76 % (163)	53.66 % (22)	76.4 % (123)	76.58 % (121)		
Male % (N)	26.24 % (58)	46.34 % (19)	23.6 % (38)	23.42 % (37)		
Education					χ^2 (5) = 8.279, $p = 0.142$	χ^2 (5) = 11.126, $\boldsymbol{p} = \mathbf{0.049}^*$ $V = 0.236$
Primary school or lower % (N)	0.90 % (2)	2.44 % (1)	0.62 % (1)	0 % (0)		
Vocational school without high school diploma % (N)	1.81 % (4)	2.44 % (1)	1.24 % (2)	1.27 % (2)		
High school diploma or equivalent % (N)	23.53 % (52)	36.59 % (15)	22.36 % (36)	22.15 % (35)		
Bachelor's or Master's degree % (N)	67.87 % (150)	51.22 % (21)	70.19 % (113)	72.52 % (113)		
Doctorate (PhD) % (N)	4.07 % (9)	2.44 % (1)	4.35 % (7)	3.80 % (6)		
Other % (N)	1.81 % (4)	4.88 % (2)	1.24% (2)	1.27 % (2)		

*p < 0.05 **p < 0.01***p < 0.001.

2.2. Measurements and design

2.2.1. Cross-sectional phase

The first, cross-sectional phase of the study contained questionnaires assessing trait-level constructs, which are not analyzed in the present paper. Participants also provided demographic information and answered questions regarding their socioeconomic status, living arrangements and exercise habits.

2.2.2. ESM phase

2.2.2.1. Negative affect and unpleasantness of a recent event. In the two-hourly surveys, we asked participants to evaluate their momentary affective states on a 6-point Likert-scale ranging from 'not at all' to 'completely'. As positive-valenced affective states, we included *calm, enthusiastic, cheerful,* and *active*, whereas the negative states evaluated were *sad, afraid, upset, angry, worried,* and *irritated*. Items and their scaling were selected based on the dimensional model of emotions (axes of arousal and valence; Russell, 2003) and previous studies (Brans, Koval, Verduyn, Lim, & Kuppens, 2013; Bringmann et al., 2016; Wichers, Groot, & Psychosystems ESM Group EWS Group, 2016). In order to fully cover the valence-arousal dimensions (Russell, 2003) and following previous works on emotional reactivity (Pe et al., 2015), we selected only negative and positive affective states with high arousal (angry, cheerful, respectively) as well as negative and positive emotional states with low arousal (sad, calm, respectively) to test our specific hypotheses.

Additionally, during each ESM session, we asked participants to rate the most significant event they experienced during the past two hours on a 7-point Likert scale, 1 being 'not at all pleasant' and 7 indicating 'entirely pleasant'. We reversed the values of this item to capture the magnitude of event-unpleasantness.

2.2.2.2. Cognitive control. For the assessment of momentary cognitive control, participants had the option to step further to complete two short tasks, a 2-back (Cohen, 1997; Kirchner, 1958) and a Go/no-go (Gomez, Ratcliff, & Perea, 2007) task. With the 2-back task, we aimed to capture working memory updating performance by asking participants to identify stimuli identical to the one presented two trials back (i.e., targets). A sequence of 60 digits (with a 0.5-s interval) appeared on the screen for 1 s in randomized order (consecutive target trials could occur in both tasks), and participants were instructed to click/tap anywhere on the screen whenever they saw a target digit. These made up 25% of all trials.

The Go/no-go task was used to assess inhibitory control performance. Participants were presented 30 'X' and 30 'O'-shaped stimuli for 0.35 s each (with inter-stimulus intervals randomly varying between 0.2 and 1 s) in randomized order and were instructed to click/tap anywhere on the screen when seeing 'O's but refrain from responding when 'X's appear, requiring them to withhold response tendencies (based on Criaud & Boulinguez, 2013).

The tasks were programmed using PsychoPy (Peirce et al., 2019) and were hosted on pavlovia.org, which presents tasks in a web browser (either on a smartphone or a computer). For both cognitive tasks, we computed the Signal Detection Theory sensitivity measure d-prime (d'; Huang & Ferreira, 2020; Peterson, Birdsall, & Fox, 1954) as a dependent variable. D-prime is a sensitivity indicator that reflects the distance between the two distributions of signals and signal plus noise and holds the Z value of the hit-rate (e.g., Go response to Go stimulus) minus the false-alarm rate (e.g., Go response to No-go stimulus) (Huang & Ferreira, 2020). A multi-stage screening protocol was applied to only include valid data for momentary 2-back and Go/no-go tasks, for details see 'Cognitive control task screening' in the Supplementary Materials. Participants used their own devices (smartphones/computers) to respond to the questionnaires and the behavioral tasks.

Moreover, we examined 2-back and Go/no-go d-prime scores' reliability for between and within individuals. For between-individual reliability, we calculated intraclass correlation coefficients (ICC) for the two tasks' d-prime scores (ICC [2-back d-prime] = 0.66, ICC [Go/no-go d-prime] = 0.58). These results show that about 60–65% of overall variation in cognitive control task performance was due to differences between individuals.

For within-individual reliability of centered cognitive control d-prime scores, we used the Spearman-Brown reliability estimate with split-half correlations including 100 random samples: for each testing occasion, we randomly split data into two halves, stratified by trial type (go/no-go or target/non-target for the Go/no-go and the 2-back task, respectively). This correlation quantifies the similarity of within-person centered scores obtained from two random halves of each testing occasion, and shows the consistency of performance *throughout* single testing occasions. Within-individual reliability was acceptable for both Go/no-go (split-half r coefficients; Mean [min-max] = 0.58 [0.55–0.60] and 2-back (split-half coefficients [r]; Mean [min-max] = 0.55 [0.53–0.59]) d-prime scores. Thus, both tasks were able to reliably capture variation within-individuals. For further details on reliability analyses see https://osf.io/htx9p/.

2.2.3. Design

We used the browser-based application *formr.org* (Arslan, Walther, & Tata, 2020) for collecting time-series data through an experience sampling design. The cognitive control tasks were programmed using PsychoPy (Peirce et al., 2019) and hosted by *pavlovia.org* that could be accessed with a smartphone or a computer through a web browser. Individuals agreeing to participate in the study received regular automatic emails from *formr.org* containing a link to the upcoming survey. The design of the study is depicted in Fig. 1 and described in detail in 'Design' in the Supplementary Materials.

2.2.4. Statistical analyses

Analyses were performed with R (v4.2.1; R Core Team, 2022) in RStudio (v2022.07.1; RStudio Team, 2022). The final two datasets contained 2494 observations for Go/no-go and 2641 observations for 2-back with complete data regarding momentary cheerfulness, calmness, anger, sadness, d-prime scores of the given cognitive control task as well as event-unpleasantness. Since momentary affective states were measured at the ordinal level (via 6-point Likert-scales), we fitted two sets of cumulative link mixed models for negative and positive affective states using the 'ordinal' R package's (v2022.11–16; Christensen, 2022) function 'clmm'.

We included each positive and negative affective state as dependent variables, while event-unpleasantness was entered as a predictor variable. We used the statistical relationship between affective states and the unpleasantness of an event to capture emotional reactivity (see Myin--Germeys et al., 2001). Operationalizing emotional reactivity relies on the following assumptions: if someone shows increased negative emotions after facing something unpleasant, the unpleasant event is likely to have caused the change in emotions. While if someone does not show increased negative emotions after a similarly unpleasant experience, it is likely that the individual regulated their emotions (Gross, 1998; Pe et al., 2015). D-prime scores (calculated by the 'd-prime' function embedded in R package 'psycho'; Makowski, 2018) of cognitive control tasks were also added to the models in interaction with event-unpleasantness. D-prime scores of 2-back and Go/no-go tasks were entered in separate models.

In order to capture the effects of within-person fluctuations, event-unpleasantness and d-prime scores of cognitive control performance were within-person centered (see Hamaker & Grasman, 2015). Within-person centering also provides a straightforward interpretation of the main effects of cognitive control performance and event-unpleasantness. Since a within-person centered zero score indicates each individual's average level, the interaction term in the regression equation is zero if the value of any predictor involved in the interaction is at the individual's average level. Thus, the main effects of cognitive control/event-unpleasantness can be interpreted as their association with the outcome emotional state while holding cognitive control/event-unpleasantness constant at each individual's average performance, respectively. Finally, all models were detrended by the number of prompts (beeps) within days and the number of days and adjusted for age and sex (both being plausible confounders of emotional reactivity and/or cognitive control, see Domes et al., 2010; Gaillard, Fehring, & Rossell, 2021; Sharp, Scott, Mehta, & Wise, 2006; Silvers et al., 2012).

The models included random intercepts per participant and random slopes for the main effects of d-prime scores of cognitive control performance and event-unpleasantness and their interaction. In the case of convergence issues (when cheerfulness was the dependent variable), we simplified the model either by simplifying the random effect structure and/or omitting to detrend. Indicators of the goodness of fit were marginal (variance explained by fixed effects) and conditional R^2 (variance explained by random and fixed effects). By using the 'clmm2' function of the 'ordinal' package (Christensen, 2022) the assumptions of proportional odds were tested and met for each model. Data and code for the analyses are publicly available on the Open Science Framework: https://osf.io/htx9p/.

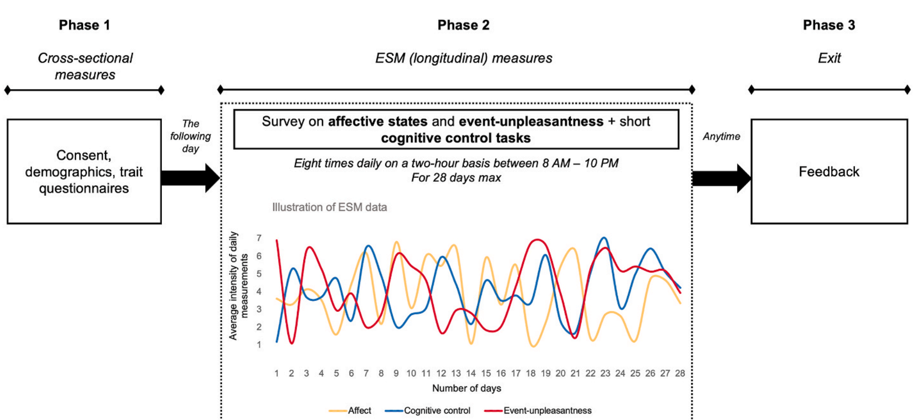

Fig. 1. Study design. Phase 1: Upon entering the study, participants were asked to complete a survey containing trait-level questionnaires and assessing demographic information. At the end of this section, participants could decide whether they wanted to take part in the ESM phase of the study, starting the next morning. **Phase 2**: Participants received 8 two-hourly prompts (beeps) daily between 8:00 a.m. and 10:00 p.m. These short, 5-min sessions included the surveys mentioned above, related to momentary affective states and event-unpleasantness, besides other items not analyzed in the present study. Then, participants were automatically redirected to *pavlovia.org* to complete the two short cognitive tasks described above, each taking approximately 1.5 min. The order of the tasks was randomized each time. Every third day, participants also received a 5-min survey exploring depressive symptoms, stressful events, support, and environmental resources in the past 3 days. This was received at 6:00 p.m. and could be completed until 10:00 p.m. No other ESM prompt (beep) was sent later those days, with the next email sent at 8:00 a.m. the following morning. Those surveys are not included in the present analysis. The yellow, blue, and red lines are an example to illustrate the fluctuation of the daily measurements of affect, cognitive control, and event-unpleasantness throughout the course of the study. **Phase 3**: Participants could take part in the ESM phase for up to 28 days, but had the option to quit at any point. After a minimum of 7 days of participation, they could choose to receive feedback containing figures about the daily fluctuation of their sleep quality and quantity, as well as their negative and positive affective states. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results

We fit two sets of cumulative link mixed models (one predicting *sadness* and *anger* by *event-unpleasantness* as well as 2-back and Go/no-go d-prime scores in separate models; and another set predicting *cheerfulness* and *calmness* by *event-unpleasantness* and the same predictors) in order to test the within-individual association between cognitive control and emotional reactivity (see Tables 2 and 3 and Fig. 2 for summarized results).

3.1. Sadness-reactivity in association with response inhibition and working memory updating performance within individuals

First, we tested whether fluctuations in response inhibition predicted sadness reactivity in daily life (see Table 2). We entered Go/no-go d-prime scores in interaction with event-unpleasantness as predictors of sadness. Event-unpleasantness in the preceding two hours positively affected momentary sadness (holding Go/no-go performance constant at the individual's average), indicating negative emotional reactivity. Regarding the moderation of negative emotional reactivity by cognitive control, the interaction between Go/no-go performance and event-unpleasantness was not significant. Nevertheless, Go/no-go d-prime scores had a negative main effect on sadness. That is, better performance in response inhibition predicted lower levels of sadness within individuals while holding event-unpleasantness constant at an individuals' average level (since the main effect of event-unpleasantness and the interaction term both become zero when within-person centered event-unpleasantness takes the value of zero).

Second, we investigated whether working memory updating predicted sadness reactivity within individuals (see Table 2). This time, the predictors were the 2-back d-prime score, event-unpleasantness, and their interaction. Again, event-unpleasantness significantly predicted sadness, while holding 2-back performance constant at the individual's average. Moreover, the main effect of 2-back performance showed that working memory was negatively related to sadness. That is, if individuals showed better working memory updating compared to their average, they experienced a lower level of sadness if event-unpleasantness was held constant at the individual's average. Notably, the degree of emotional reactivity was related to within-person fluctuations in working memory updating: the interaction of 2-back d-prime score and event-unpleasantness positively predicted sadness (2-back performance moderated event-unpleasantness' effect on sadness). This implies that contrary to our expectations, when participants had *better* momentary working memory updating compared to their average, they experienced *more intense* sadness in response to event-unpleasantness.

3.2. Anger-reactivity in association with response inhibition and working memory updating performance within individuals

Then, to see how cognitive control was associated with anger reactivity, we refitted the above models with anger as the outcome variable (Table 2). As in the previous models, these analyses established that anger reactivity was observable since event-unpleasantness predicted increased anger, while holding cognitive control performance constant at the individual's average. Go/no-go performance had no significant main effect on anger, nor was its interaction with event-unpleasantness significant. Importantly, 2-back performance had a significant negative main effect on anger. That is, while holding event-unpleasantness constant at an individuals' average level, better working memory updating was related to reduced anger. Regarding the moderation of anger reactivity by working memory updating, our expectations were again contradicted: 2-back performance showed a significant interaction with event-unpleasantness in predicting anger: *higher* working memory updating predicted *more intense* anger-related emotional reactivity within individuals.

3.3. Positive affectivity and reactivity in association with response inhibition and working memory updating performance within individuals

Finally, to examine the relationship between positive emotional reactivity and cognitive control within individuals, we predicted positive affective states (cheerfulness and calmness) in the second set of models (see Table 3). In all models, event-unpleasantness significantly decreased the probability of experiencing higher levels of cheerfulness and calmness (while holding cognitive control performance constant at the individual's average); that is, we established positive emotional reactivity as well. However, neither Go/no-go nor 2-back performance were significant moderators of positive emotional reactivity. In addition, the main effects of 2-back and Go/no-go performance were not significant in predicting either cheerfulness or calmness.

3.4. No evidence that momentary cognitive control moderates the association of depression or trait rumination with negative affect

Although the focus of this study was on within-individual processes, we conducted additional analyses where we tested whether cognitive control fluctuations also moderate the expression of depressive symptoms and trait rumination in daily life. Specifically, we fitted additional models to test whether momentary cognitive control performance moderated the association of sadness and anger with individual differences in depressive symptoms and rumination. No evidence was found that momentary cognitive control performance moderates the effect of depressive symptoms and rumination (measured at the first, cross-

Table 2
Results of cumulative link mixed models for the associations of negative emotional reactivity and cognitive control.

Predictors	In predicting:							
	Sadness		Sadness		Anger		Anger	
	Odds Ratios	*CI*	*Odds Ratios*	*CI*	*Odds Ratios*	*CI*	*Odds Ratios*	*CI*
Age	**0.96****	0.93–0.99	**0.96****	0.93–0.99	**0.97***	0.94–1.00	0.98	0.95–1.02
Sex [Male]	0.89	0.32–2.43	0.84	0.31–2.32	1.09	0.44–2.65	0.92	0.35–2.41
Beep	1.01	0.96–1.06	*1.03*	*0.99–1.08*	0.97	0.91–1.02	0.96	0.90–1.02
Day	1.02	0.99–1.05	*1.03*	*0.99–1.06*	0.99	0.96–1.03	0.99	0.95–1.03
Event-unpleasantness	**1.98*****	**1.67–2.34**	**2.13*****	**1.79–2.54**	**2.68*****	**2.21–3.24**	**2.98*****	**2.36–3.77**
Go/no-go d'	**0.73***	**0.56–0.96**			0.89	0.60–1.31		
2-back d'			**0.79+**	**0.61–1.02**			**0.56****	**0.39–0.82**
Event-unpleasantness × Go/no-go d'	0.96	0.76–1.22			1.26	0.93–1.71		
Event-unpleasantness × 2-back d'			**1.31****	**1.08–1.59**			**1.71*****	**1.32–2.21**
N	161		158		161		158	
Observations	2494		2641		2494		2641	
Marginal R^2/Conditional R^2	0.086/0.718		0.092/0.717		0.162/0.656		0.166/0.706	

+*p* < 0.1; **p* < 0.05; ***p* < 0.01; ****p* < 0.001.

Table 3
Results of cumulative link mixed models for the associations of positive emotional reactivity and cognitive control. In Model 6, number of beeps and days were not included due to convergence issues.

Predictors	In predicting:							
	Cheerfulness		Cheerfulness		Calmness		Calmness	
	Odds Ratios	*CI*	*Odds Ratios*	*CI*	*Odds Ratios*	*CI*	*Odds Ratios*	*CI*
Age	1.01	1.00–1.03	1.01	0.99–1.02	1.03	1.01–1.05	1.03	1.01–1.05
Sex [Male]	**2.10****	1.26–3.52	**2.30****	1.30–4.08	**1.90**$^{+}$	0.94–3.85	**1.84**$^{+}$	0.90–3.75
Beep	0.98	0.95–1.02	*NA*	*NA*	**1.04***	1.00–1.08	**1.04***	1.00–1.08
Day	1.01	0.99–1.03	*NA*	*NA*	0.99	0.97–1.01	0.98	0.96–1.01
Event-unpleasantness	**0.59*****	0.55–0.63	**0.56*****	0.51–0.62	**0.56*****	0.51–0.62	**0.55*****	0.50–0.61
Go/no-go d'	1.08	0.86–1.35			0.99	0.83–1.17		
2-back d'			0.97	0.88–1.08			1.09	0.95–1.25
Event-unpleasantness × Go/no-go d'	0.95	0.84–1.08			1.09	0.95–1.24		
Event-unpleasantness × 2-back d'			0.96	0.87–1.07			1.01	0.90–1.15
N	161		158		161		158	
Observations	2494		2641		2494		2641	
Marginal R^2/Conditional R^2	0.093/0.397		0.093/0.441		0.093/0.545		0.087/0.574	

$^{+}p < 0.1$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

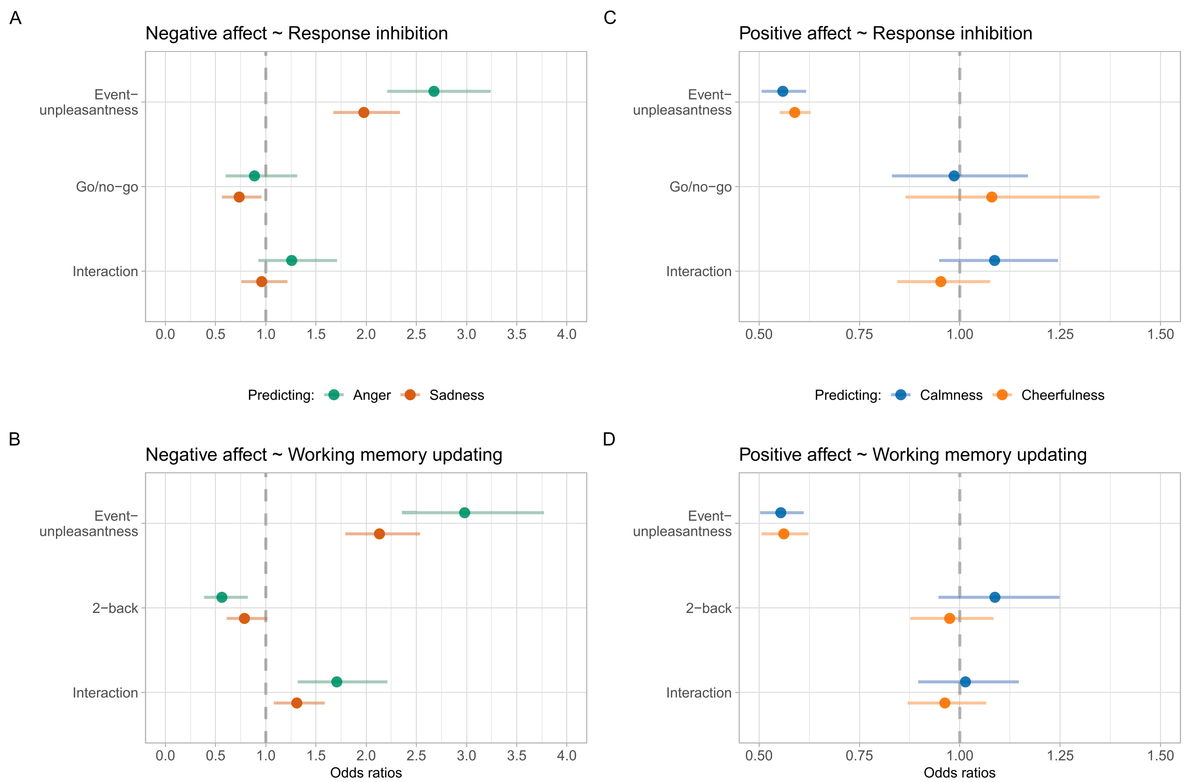

Fig. 2. Summarized results of all models. The colored points represent the estimated odds ratios of the cumulative link mixed models. Error bars show confidence intervals. Event-unpleasantness significantly predicted each emotional state, which implies we successfully modeled emotional reactivity in all models. Go/No-go performance significantly lowered the chance of experiencing sadness **(A)**, while 2-back performance significantly lowered the chance of experiencing anger **(B)** (cognitive control performance was captured by d-prime scores). Interactions between 2-back performance and event-unpleasantness positively predicted higher levels of anger and sadness **(B),** which suggests working memory updating moderated negative emotional reactivity within individuals. Interactions between cognitive control performance and event-unpleasantness were not significant in the rest of the models **(A, C, D)**. Cognitive control performance did not predict positive emotional states or positive emotional reactivity **(C, D)**.

sectional phase of the study) on negative affective states. More detailed information on the measurement tools, models and results can be found in the Supplementary Materials.

4. Discussion

This study investigated the within-individual associations between two dimensions of cognitive control (response inhibition and working memory updating) and emotional reactivity (intensity of negative and positive affective states induced by event-unpleasantness). We expected that better momentary working memory updating and response inhibition performance would predict less intense negative emotional responses to event-unpleasantness. Aligning with our hypotheses, better working memory updating performance *per se* was associated with decreased anger (and tended to predict lower levels of sadness as well), while holding event-unpleasantness constant at each individual's average level. Based on these findings, within-individual increases in momentary working memory updating are linked to reduced negative affectivity, when individuals rate recent events as on average unpleasant. However, contrary to our expectations, 2-back performance positively moderated the within-individual association between event-unpleasantness and negative affective states. This implies that increases in working memory updating within individuals are related to a more negative emotional response to events rated as more unpleasant.

Against our prior assumptions, no significant interaction effect was found between momentary Go/no-go performance and event-unpleasantness in predicting sadness and anger. Still, Go/no-go performance negatively predicted sadness if event-unpleasantness was held constant at each individual's average level. Furthermore, we did not detect any evidence regarding the effects of cognitive control performance on the associations between event-unpleasantness and positive affective states (cheerfulness and calmness) at the within-individual level.

Our main finding indicates that the within-individual relationship between working memory updating and negative affective states is associated with momentary event-unpleasantness. Better working memory updating predicted lower negative affect if event-unpleasantness was held constant at each individual's usual level, while with increases or decreases in event-unpleasantness, working memory updating was associated with a stronger coupling between event-unpleasantness and negative emotions (i.e., increased emotional reactivity). Previous results regarding this question have been controversial. On the one hand, better baseline working memory was associated with adaptive emotion regulation. It was related to decreased negative affect within individuals (Pe et al., 2015), and higher working memory performance predicted lower negative affect within individuals on a daily basis (Brose, Schmiedek, Lövdén, & Lindenberger, 2012) and stress (Sliwinski, Smyth, Hofer, & Stawski, 2006). In contrast, other research found *better* baseline working memory performance to be related to *more intense* negative emotional reactivity within individuals (Pe et al., 2015). Moreover, it has also been suggested that exposure to stress could significantly reduce the efficiency of cognitive emotion regulation (Raio, Orederu, Palazzolo, Shurick, & Phelps, 2013).

Second, although we found no associations between performance on response inhibition and negative emotional reactivity, our analyses revealed that higher-than-average momentary response inhibition predicted lower levels of momentary sadness within individuals, if the level of event-unpleasantness was held constant at an individuals' average level. In line with this result, in earlier studies, better response inhibition was related to lower frequency of rumination (De Lissnyder, Derakshan, De Raedt, & Koster, 2011), whereas it was positively related to the efficient implementation of reappraisal (Cohen & Mor, 2018). Furthermore, self-reported behavioral suppression of emotional responses was associated with less intense negative affect at the within-individual level on a few-day basis (Rónai & Polner, 2022). However, other studies did not reveal associations between response inhibition and adaptive emotion regulation (see Pruessner et al., 2020, for a review). As argued elsewhere, cognitive control does not flatten emotional reactivity but rather contributes to adaptive regulation, such as reappraisal across individuals (Cohen & Mor, 2018). Although we did not measure momentary reappraisal directly to test its interrelations with cognitive control and affective functioning, our result regarding the negative within-person association between response inhibition and sadness may still support the latter argument.

As shown by our data, there were no significant associations between momentary fluctuations of cognitive control and positive affectivity or emotional reactivity. Previous studies highlighted positive associations between cognitive flexibility (i.e., the shifting dimension of cognitive control) and positive affectivity across individuals (Dreisbach & Goschke, 2004; Liu & Wang, 2014). Since we did measure both inhibition and updating *but not shifting* in this study, the lack of significant results can be explained by the fact that positive affect may instead be related to cognitive flexibility within individuals. This should be tested by future studies. Yet, other explanations might also be conceivable. For example, Brose et al. (2014) found that better working memory updating predicted higher positive affect within individuals *on a daily basis* over a period of about 100 days. We investigated the latter relation on a two-hour basis over a somewhat shorter period. Therefore, it is also plausible that positive affectivity and cognitive control are associated at a somewhat longer timescale instead. Moreover, it has also been proposed that reward motivation can strongly influence the association between cognitive control and positive affectivity (Chiew, 2021) since it significantly amplifies adaptive emotion regulation (Kelley, Glazer, Pornpattananangkul, & Nusslock, 2019).

Previous studies show that better cognitive control performance is strongly associated with adaptive emotion regulation (Cohen & Mor, 2018; Hendricks & Buchanan, 2016; Ochsner & Gross, 2005; Pruessner et al., 2020); still, they also raise several questions and issues. First, this association seems not entirely consistent across studies: *better* baseline working memory performance predicted *higher* recovery from negative affective states after the recall of a negatively-valenced event within individuals (Pe et al., 2015). On the other hand, *higher* trait-level working memory performance was associated with *higher* anger reactivity, but it also facilitated emotional recovery, effective reappraisal and dampened the effect of rumination on negative affect (Pe et al., 2013, 2015).

In line with these studies, our results also showed that the associations between momentary working memory updating performance and negative affectivity are complex: better performance on Go/no-go and 2-back tasks *in isolation* was associated with lower levels of sadness, if individuals experienced *average* event-unpleasantness compared to themselves. In the final sample, 0 was the most frequent value for centered event-unpleasantness (median and mode = 0), that is, in line with the literature, *better* momentary cognitive control was associated with *lower* levels of sadness within individuals *most of the time*. However, when event-unpleasantness increased, the statistical relationship between cognitive control and negative emotions was reversed compared to what was described above: *higher* 2-back performance *in combination with higher* event-unpleasantness predicted *increased* experience of negative affect.

One may speculate about the underlying mechanisms. If recent events are rated as more unpleasant than usual, better working memory may contribute to *the further maintenance* of negative mental contents, thereby it may increase the intensity of emotional reactivity. On the other hand, if event-unpleasantness was at an individuals' average level, higher working memory can promote *updating for the replacement* of negative information, leading to reduced negative emotionality. Therefore, the results of this study may also imply that event-unpleasantness should be considered when interpreting the within-individual relationship between cognitive control and momentary affective states.

The direction of causality between emotional reactivity and cognitive control can be an open issue (Inzlicht, Bartholow, & Hirsh, 2015; Pe et al., 2015). Although we built on the assumption that cognitive control has a causal effect on emotion regulation (Hoorelbeke et al., 2016, 2023), still, one may argue that increased negative emotional reactivity could have causally increased working memory capacity (Martin & Kerns, 2011). However, based on meta-analyses and large-scale replication studies, acute stress and emotion induction seem to have a negative or a zero causal effect on working memory (Shields, Sazma, & Yonelinas, 2016; Souza et al., 2021; Xie, Ye, & Zhang, 2022). Therefore, it is unlikely that a positive causal effect of stress reactivity on working memory would explain our results. Although experimental studies will be more decisive about causality, with the above cited evidence, interpreting the association as an indication for the causal effect of cognitive control is more plausible.

Based on this pattern of findings, we argue that the relationship between cognitive control and negative emotionality can only be interpreted by taking the evaluation of the context into account. Accordingly, we refute the general claim that better cognitive control functioning is universally associated with reduced negative emotions and enhanced positive emotions, i.e., adaptive emotion regulation

(Cohen & Mor, 2018; Hendricks & Buchanan, 2016). By extension, our conclusion also challenges the applicability of cognitive control training in the internalization of adaptive emotion regulation strategies (Cohen & Mor, 2018; Schweizer et al., 2013). In line with this, studies investigating cognitive control efficiency in emotion regulation have provided somewhat mixed results. For instance, it has been found that cognitive control training does not have short-term beneficial effects when added to treatment-as-usual for depressed patients (Ferrari et al., 2021).

Moreover, other studies suggest that cognitive control training might positively impact adaptive emotion regulation, whereas its overall efficiency is limited in daily life functioning (Hoorelbeke et al., 2016, 2023). In contrast, other studies firmly support the benefits of cognitive control training in adaptive emotion regulation (Hendricks & Buchanan, 2016; Joormann & Quinn, 2014; Schweizer et al., 2013; Xiu et al., 2018) as well as in reducing vulnerability to anxiety and depression (Beloe & Derakshan, 2020; Grol et al., 2018). As suggested by the findings of our study, these controversial findings might be due to the fact that the connection between cognitive control and affective functioning relies heavily on contextual factors, the available emotion regulation strategies, and motivation.

According to previous findings, emotion regulation as a trait may predict momentary affective functioning (Krkovic, Clamor, & Lincoln, 2018). However, others suggest that it is the distribution of states themselves that can be interpreted as traits (Fleeson & Jayawickreme, 2015). Following Fleeson and colleagues' approach, we speculate that, in fact, here we demonstrated that momentary cognitive control changes are potential causes of fluctuation in affective states in everyday life. It is important to underline that the aim of this study was to test hypotheses about within-person associations of cognitive control and emotional reactivity, independently from trait-level constructs. Our rationale was the following: as the aim of psychological interventions is to induce within-individual changes, the generalizability of between-individual findings needs to be established at the within-individual level (see Fisher et al., 2018). Nevertheless, we explored whether momentary cognitive control moderated the association of depressive symptoms and trait-rumination with negative affect. We did not find any significant moderation (see Supplementary Materials).

A limitation of this study is that the final sample mainly included highly educated female individuals, which limits the generalizability of the findings. Furthermore, significant differences were found between the samples included and not included in the final datasets. However, these differences were rather small (see Table 1 for effect sizes). We did not have the financial means to provide compensation to the participants in this study - as participation was voluntary, data regarding extreme affective states or cognitive control performance may be underrepresented in the samples, which may bias our results. Finally, the lack of sufficient number of consecutive observations did not allow us to analyze emotional recovery, another aspect of real-life emotional regulation which might be moderated by working memory capacity (Pe et al., 2015). Future research should address whether our findings generalize to emotional recovery.

Since most neuropsychiatric conditions are not static processes, it seems essential to understand how contextual factors affect the dynamics of cognition and affective functioning that in turn influence the emergence and maintenance of symptoms (Gillan & Rutledge, 2021; Hitchcock, Fried, & Frank, 2022). Thus, in this study, we evaluated the effect of fluctuations in cognitive control on the temporal association between event-unpleasantness and momentary affective states. Revisiting the issue of between- and within-participant levels of exploration proposed by previous studies (Fisher et al., 2018; Gillan & Rutledge, 2021; Hitchcock et al., 2022), we found significant effects of the state component of cognitive control on emotional reactivity (also see Faßbender, Meyhöfer, & Ettinger, 2023 for state-trait modeling of inhibitory control). We can conclude that the interconnections between affective functioning and cognitive control display a highly complex picture within individuals - and in this picture, the subjective unpleasantness of events emerges as a salient detail that cannot be ignored.

In summary, this study examined the within-individual relationships between temporal fluctuations in cognitive control and emotional reactivity in narrow two-hour measurement windows. Our results are informative about the utility and validity of the assessment of momentary cognitive control in predicting the intensity of momentary emotional responses. An important practical implication of this study is that we may get closer to the personalized prediction of changes in clinically relevant psychological phenomena through digital monitoring of cognition-, stress- and affect-related processes by simple behavioral and self-reported assessments.

Transparency and openness

Study designs and analysis plans were not preregistered. Data and code for the analyses are publicly available on the Open Science Framework at https://osf.io/htx9p/. Participation was voluntary, and participants provided informed consent. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. The study was approved by the United Ethical Review Committee for Research in Psychology, Hungary (reference number: 2021–38). Additional information on ethical standards can be found in the Supplementary Materials. We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. We have reported all simulations or other analyses we conducted as part of the work.

CRediT authorship contribution statement

Levente Rónai: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Flóra Hann:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. **Szabolcs Kéri:** Funding acquisition, Writing – review & editing. **Ulrich Ettinger:** Conceptualization, Writing – review & editing. **Bertalan Polner:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Software, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to the data and scripts in the 'Title' and the 'Manuscript' document.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brat.2023.104462.

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