

# Individual differences in self-reported self-control predict successful emotion regulation

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## Abstract

Both self-control and emotion regulation enable individuals to adapt to external circumstances and social contexts, and both are assumed to rely on the overlapping neural resources. Here, we tested whether high self-reported self-control is related to successful emotion regulation on the behavioral and neural level. One hundred eight participants completed three self-control questionnaires and regulated their negative emotions during functional magnetic resonance imaging using reappraisal (distancing). Trait self-control correlated positively with successful emotion regulation both subjectively and neurally, as indicated by online ratings of negative emotions and functional connectivity strength between the amygdala and prefrontal areas, respectively. This stronger overall connectivity of the left amygdala was related to more successful subjective emotion regulation. Comparing amygdala activity over time showed that high self-controllers successfully maintained down-regulation of the left amygdala over time, while low self-controllers failed to down-regulate towards the end of the experiment. This indicates that high self-controllers are better at maintaining a motivated state supporting emotion regulation over time. Our results support assumptions concerning a close relation of self-control and emotion regulation as two domains of behavioral control. They further indicate that individual differences in functional connectivity between task-related brain areas directly relate to differences in trait self-control.

**Key words:** self-regulation; reappraisal; fMRI; functional connectivity; amygdala

## Introduction

Traditionally, emotion regulation has been studied apart from self-control. Nevertheless, it is generally assumed that both types of control have similarities, as both involve the overriding of automatic responses in favor of controlled ones. Furthermore, in everyday life they are often interconnected: Imagine your overall long-term goal to lose weight is challenged by a disgusting meal replacement shake. In situations like this, regulating your emotions, for instance by reappraising the shake as primarily healthy and not disgusting, sub-serves successful self-control. In the past, both types of control have been studied extensively on their own, but not in conjunction. Here we set out to study their relation in a within-subject design.

## Emotion regulation

The ability to regulate emotions allows for adapting one's thoughts and feelings according to personal preferences and social situations (Koole, 2009). It has been related to mental and physical health (Gross and Muaoz, 1995; Salovey et al., 2000), greater well-being and higher socioeconomic status (SES) (Côté et al., 2010). Emotion regulation refers to the up- or down-regulation of positive or negative emotions by applying one of several strategies. Cognitive reappraisal is one of the most effective ones and therefore the focus of the current study (Gross 1998a). Two different forms of reappraisal have been described in Ochsner et al. (2004). Although 'reinterpretation' involves a transformation and reinterpretation of the emotional content of a stimulus, 'distancing' (used in this study) alters the personal relevance.

Reappraisal has been shown to successfully decrease the intensity of negative feelings as indicated by subjective ratings (e.g. Ochsner et al., 2002), peripheral physiological measures of negative affect (e.g. Gross 1998a) and activation of brain regions related to the processing of salient stimuli such as the amygdala (e.g. Kim and Hamann 2007). However, reappraisal requires cognitive resources as reflected in the recruitment of a cortical network, comprising the dorsolateral (DLPFC) and ventrolateral (VLPFC) prefrontal cortex (PFC), medial parts of the PFC (mPFC) and the inferior parietal lobe (IPL) (Ochsner et al., 2004; Kanske et al., 2010; McRae et al., 2012; Dörfel et al., 2014). Studies showed that the stronger this fronto-parietal network is activated, the more amygdala activity is attenuated (Ochsner et al., 2002; Walter et al., 2009). Psychophysiological interaction (PPI) analyses further revealed that stronger functional connectivity between the amygdala and prefrontal regions during reappraisal is related to more successful down-regulation of negative emotions (Banks et al., 2007; Erk et al., 2010a; Kanske et al., 2010; Schardt et al., 2010).

Patient studies have likewise shown that interindividual differences in the degree of coactivation between sub-regions of the PFC and the amygdala are related to emotion regulation success. For instance, while healthy controls activate the inferior frontal gyrus and ventromedial PFC (vmPFC) to down-regulate their amygdala activity, this prefrontal-amygdala circuit breaks down in patients with major depression (Johnstone et al., 2007; see also Erk et al., 2010a) and also impulsive-aggressive individuals with borderline personality disorder (New et al., 2007). Finally, in line with assuming that stronger interactions between PFC and amygdala reflect stronger control over negative emotions, stronger PFC-amygdala connectivity has been shown to be associated with lower trait anxiety in healthy individuals (Kim and Whalen, 2009).

## Self-control

Self-control can be described as the ability to pursue overarching goals despite short-term temptations, distractions or aversive states (Tangney et al., 2004; Baumeister et al., 2007). This encompasses the capacity to intentionally alter one's thoughts and behavioral response tendencies, thus overriding impulsive behavior in different domains (Tangney et al., 2004). The concepts of self-controlled and impulsive behavior oppose each other but both contribute whenever we make a decision (e.g. Bechara, 2005; but see Ludwig et al., 2013). Individuals with high self-reported self-control achieve higher grades, are more successful in controlling their eating behavior and show generally stronger health-promoting behavior and well-being (Tangney et al., 2004; Kreutz et al., 2008; Hofer et al., 2011). In contrast, higher impulsivity is associated with alcohol consumption and aggression (Dahlen et al., 2005; Hair and Hampson, 2006).

The neural correlates of self-control have been studied mainly in the field of decision-making. Overall, these studies support the assumption that self-control is related to effortful top-down modulation by higher-order PFC regions over lower-order PFC regions or sub-cortical areas, and that this modulation is indicated by changes in activity and functional connectivity. For example, individuals who exerted self-control to favor healthy over unhealthy food, showed increased DLPFC activation and reduced value signals for unhealthy food supposedly encoded in the vmPFC (Hare et al., 2009). Importantly, these value-related signals were modulated by changes in functional connectivity between both regions, indicating that specifically the functional coupling between brain areas plays a crucial role in self-controlled behavior. In line with this, Peters and Büchel (2010) showed that reducing individuals' impulsivity experimentally in a temporal discounting paradigm was associated with modulation in functional PFC connectivity. In this study, future thoughts about intentions regarding the offered amount of money were induced. This manipulation did not only reduce the discounting of delayed rewards but was also associated with differences in the activity and functional connectivity between PFC and sub-cortical regions. Similarly, Kober et al. (2010) showed that thinking about long-term consequences of smoking successfully reduced craving. Also here, resisting a temptation was associated with higher activation of control-related PFC areas and mediated by reduced activity in sub-cortical areas like the striatum.

There is some evidence that the connectivity between frontal and sub-cortical networks might not only be associated with these state-related changes of self-control or impulsivity, but also with trait-related individual differences. For example, functional connectivity strength between PFC and midbrain regions not only predicts behavioral success of long-term goal pursuit but also correlates with self-reported individual impulsivity (Diekhof and Gruber, 2010; Diekhof et al., 2012).

Thus, based on previous findings there is much evidence suggesting a close overlap between self-control and emotion regulation.

## Self-control involved in emotion regulation

This assumption is supported by several observations. First, self-control and emotion regulation share a high degree of conceptual overlap. Emotion regulation is even assumed to be one form of self-control (e.g. Gross, 1998b; Muraven et al., 1998; Gross, 2007). Second, a relation between both types of control is also indicated by their correlation with similar outcome

variables such as academic success (Tangney et al., 2004; Graziano and Reavis 2007), greater health (Salovey et al., 2000; Kreutz et al., 2008) and well-being (Côté et al., 2010; Hofer et al., 2011). More direct examinations have shown that children and adults with higher self-control cope more easily with emotional distress (Gramzow et al., 2000; Gailliot et al., 2006). Similarly high self-control has been associated with greater emotional stability (Tangney et al., 2004) and the strength of self-control in children even predicts their emotional coping ability several years later (Shoda et al., 1990).

Behaviorally, it has often been observed that when a self-control task is executed after an emotion regulation task, performance is usually worse compared with when it is executed first (e.g. Muraven et al., 1998; Hagger et al., 2010). Even though it is highly debated whether this depletion effect shows up in a statistically robust manner (see Carter and McCullough, 2014 for criticism; but see Hagger and Chatzisarantis, 2014; Inzlicht et al., 2015 for reply to this criticism), proponents of its presence argue that it demonstrates shared resources by different task categories (Muraven et al., 1998). The fact that tasks involving forms of emotion regulation (e.g. expressive suppression) are commonly used to induce this depletion effect (which again is attributed to be a self-control-related effect) demonstrates the so far overall assumption that emotion regulation and self-control conceptually highly overlap.

On the brain level, areas of the fronto-parietal network involved in emotion regulation are consistently recruited in tasks requiring self-control, as outlined above (Peters and Büchel, 2011). From a simple dual-processing view, both emotion regulation and self-control are assumed to involve reflective processing presumably exerted by the PFC and intuitive evaluation by more basal brain regions. Thereby the vmPFC particularly attracts the attention, as this region is assumed to provide a link between PFC regions and the amygdala during emotion regulation (Urry et al., 2006; Etkin et al., 2011) and also takes part in valuation processes that are relevant for self-controlled behavior (Hare et al., 2009).

Whether individual differences in self-control are associated with the ability to regulate one's emotions and whether this is associated with individual differences in brain activity and/or PFC-sub-cortical functional connectivity is still an open question. Investigating spontaneous emotion regulation, Drabant et al. (2009) found a relationship between the self-reported use of reappraisal and amygdala down-regulation as well as PFC up-regulation during processing of negative emotional stimuli. Abler et al. (2007) found a similar relationship between trait reappraisal and amygdala down-regulation during the expectation of negative visual stimuli, but only in medicated depression patients and not in healthy participants. Wagner et al. (2013) reported that, compared with a non-depleted group, individuals who first exerted effortful inhibition in an attentional task showed higher amygdala reactivity and lower PFC-amygdala functional connectivity when, afterwards, passively viewing emotional stimuli. Interestingly, these authors did not find significant correlations between neural responses or connectivity and trait self-control. However, as Drabant et al. (2009) and Wagner et al. (2013) assumed that merely viewing emotional stimuli already induces spontaneous emotion regulation, their approach not to instruct a specific regulation strategy makes it difficult to interpret what participants were doing during the emotional viewing task. In the present study we predefined an explicit regulation strategy during an fMRI emotion regulation task and tested whether trait self-control, measured by questionnaires, is associated with emotion regulation ability.

Moreover, we investigated the neural mechanisms underlying this association. Most likely one might expect higher self-control to be generally related to greater emotion regulation ability. Beyond this, individuals high in self-control might have access to longer lasting resources, enabling them to more successfully regulate their emotions over a longer period of time (Baumeister, 1998; but see Carter and McCullough, 2014). Also theories which do not assume that finite resources but rather switching motivational states determine how long individuals pursue a current goal, infer that the strength of executed self-control changes over time (e.g. Inzlicht et al., 2014). Thus, an association of both types of control might be expected generally or over the course of time.

However, as self-control and emotion regulation are assumed to require cognitive strategies, it is possible that a potential relation between both is based on third explanatory variables, which are generally related to controlled behavior, such as intelligence quotient (IQ) or SES (Moffitt et al., 2011), self-efficacy beliefs (Bandura et al., 1988; Stajkovic and Luthans, 1998), or general higher motivation to spend effort in task performance (Locke, 1968). Therefore, we controlled for some of these alternative explanatory variables, by assessing IQ, self-efficacy and effort-related measurements and examined whether they mediate a possible relationship between both types of control.

We expected that high self-controllers would show greater success in emotion regulation, indicated by fewer negative emotions and stronger amygdala down-regulation. Furthermore, we expected regulation success in high self-controllers to be related to increased recruitment of prefrontal regions and/or to stronger PFC-amygdala functional connectivity.

## Methods

### Participants and procedure

We analyzed data from 108 healthy (55 female) participants aged from 20 to 35 years (mean = 26.12, SD = 3.7). Further 17 participants were tested but excluded from the analysis (see Supplementary Materials). All participants were native German speakers, right handed, current or former students, had normal or corrected-to-normal vision, and no physiological or psychological conditions which may influence brain activation. Depending on their performance, participants were paid between 75 and 105€ for completing the study, which entailed several other experiments to be reported elsewhere (Supplementary Materials). Informed consent was obtained according to a protocol approved by the local ethics committee.

### Psychological measurements

**Self-control assessment.** To assess self-control comprehensively, sum scores of the Brief Self-Control Scale (BSCS; Tangney et al., 2004; German translation by Renner et al., 2009), the Self-Regulation Scale (SRS; Schwarzer et al., 1999) and the Barratt Impulsiveness Scale (BIS-11; Patton et al., 1995) were used. All three tests are internally consistent with a Cronbach's  $\alpha$  of BSCS = 0.83, SRS = 0.76 and BIS-11 = 0.83 and have a re-test reliability of BSCS = 0.87, SRS = 0.76 and BIS-11 = 0.83 (Tangney et al., 2004; Schwarzer et al., 1999; Stanford et al., 2009).

Previous research shows that the BSCS and the SRS correlate positively around  $r = 0.54$ , and negatively with the BIS-11 (BSCS:  $r = -0.52$ , SRS:  $r = -0.39$ ; Ludwig et al., 2013). In order to obtain 'one' score measuring self-control per individual, we conducted

a principal component analysis on the BSCS, SRS and BIS assessment outcomes to reduce the dimensions of the data (see 'Results' section). This value was used as a measure of self-control.

**Control variables.** Additionally, participants completed questionnaires assessing IQ ('Leistungsprüfung', Horn, 1983), self-efficacy ('Allgemeine Selbstwirksamkeitserwartung', Schwarzer et al., 1999) and motivation (BIS/BAS, Carver and White, 1994; General regulatory focus measure, Lockwood et al., 2002; For a detailed description of the selected questionnaires see Supplementary Materials). To exclude that these factors mediate a relation between self-control and emotion regulation, we tested whether they correlated with the self-control factor and the emotion regulation ratings.

## Emotion regulation task

We used an emotion regulation task based on distancing, a form of reappraisal, that has been used with some variations in several previous studies of our group (Walter et al., 2009; Erk et al., 2010a,b; Schardt et al., 2010; Dörfel et al., 2014; Gaebler et al., 2014; Lamke et al., 2014). In this paradigm (Figure 1a), participants are shown negative and neutral pictures with social content, selected from the Emotional Picture Set (Wessa et al., 2010) based on valence- and arousal-values and matched between participants (Supplementary Materials).

Participants were instructed to either watch the picture and permit the upcoming emotions, or to regulate their emotions by self-focused reappraisal, that is distancing from the displayed scene and taking the position of a neutral observer. Regulation was applied for negative pictures only, resulting in three different task conditions: watching neutral (WatchNeu), watching negative (WatchNeg) and regulating negative stimuli (RegulateNeg).

The experiment consisted of 60 trials, each of which included an instruction, a picture, a rating and a fixation phase (Figure 1a). Before the experiment, participants completed a short training session outside the scanner and were carefully instructed on how to apply distancing as a regulation strategy (Supplementary Materials).

## fMRI data acquisition and preprocessing

Whole-brain fMRI data were collected with a 3 Tesla Siemens Tim Trio MRI scanner (Siemens, Erlangen, Germany). To minimize motion, the head was fixated with cushions. Using a 12-channel head coil, functional images including 32 continuous

slices (descending) were acquired with a T2\*-sensitive one-shot gradient-echo echo-planar sequence. The following parameters were used: repetition time = 2 s, echo time = 25 ms, flip angle = 78°, field of view = 24 cm and data acquisition matrix = 64 × 64, voxel size = 3 × 3 × 3 mm and inter slice gap = 0.75 mm. Functional images were motion-corrected, realigned and unwrapped based on fieldmaps, slice-time corrected, coregistered to the anatomical data, spatially normalized to the Montreal Neurological Institute (MNI) template and smoothed with an 8-mm full width half-maximum Gaussian filter (see Supplementary Materials).

## Statistics

### Ratings and questionnaires

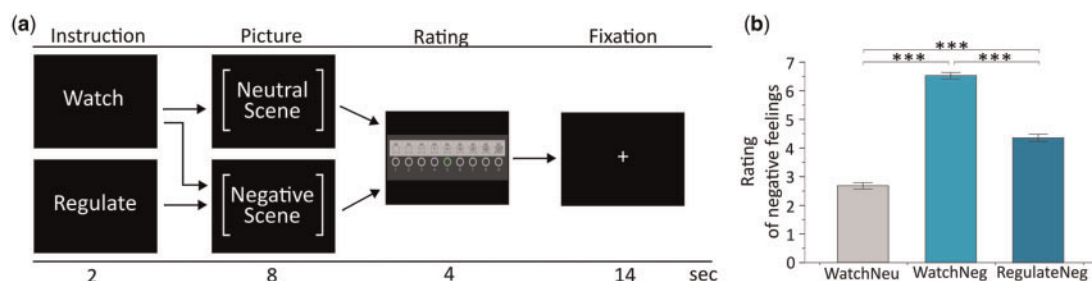
Visual inspection of histograms indicated normally distributed data. Within-subject effects were analyzed by repeated-measure analyses of variance (ANOVAs) and paired t-tests. As a measure of effect size,  $\eta^2$  is reported for ANOVAs. Associations between the self-control factor score and emotion ratings were tested by calculating Pearson's correlation coefficient  $r$ . All significance tests were performed at  $\alpha = 0.05$ .

### fMRI analysis

Pre-processed data were analyzed using the general linear model (GLM; Friston et al., 1995). Low-frequency drifts were removed using a high-pass filter (cutoff 128 s). In the GLM, we modeled the picture and fixation phase of each task condition (WatchNeu, WatchNeg, RegulateNeg) as box-car functions of specific lengths (picture = 8 s, fixation = 14 s). The instruction and rating phase were modeled together for all task conditions, with one instruction and one rating regressor as box-car functions of 2 and 4 s, respectively. Subject-specific motion parameters were included as covariates of no interest to correct for motion artifacts. Box-car functions were convolved with a canonical hemodynamic response function.

Individual contrasts between task conditions were computed at the subject-level and then taken to group-level t-tests. Unless otherwise stated we controlled for multiple comparisons by applying a combined threshold of  $P < 0.001$  uncorrected on the peak and  $P < 0.05$  family-wise error (FWE)-corrected on the cluster level.

To investigate effects of regulation on amygdala activity, analyses were restricted to *a priori* defined regions of interest (ROIs). Based on the Automated Anatomical Labeling atlas, anatomical masks of the right and left amygdala were defined. After computing the contrast of WatchNeg > RegulateNeg these



**Fig. 1.** Paradigm and rating. (a) In each trial participants either permitted their emotions during the presentation of a neutral or negative picture ('Watch') or down-regulated their emotions during presentation of a negative picture ('Regulate'). In the following rating phase, participants indicated the strength of their negative feelings on a 9-point version of the Self-Assessment-Manikin scale (1 = weak, 9 = strong; Lang, 1980). (b) Subjective ratings (mean ± SE) showed the highest negative emotions for negative pictures in the watch-condition. In the RegulateNeg-condition negative emotions were successfully down-regulated.  $n = 108$ , \*\*\* $P < 0.001$



masks were used for small volume correction (SVC) at a FWE corrected level of  $P < 0.05$ . The betas of all significantly activated voxels were extracted and mean values per amygdala, condition and participant were calculated for means of correlating them with self-report measures and for visualization purpose.

### Psychophysiological interaction

To assess connectivity between the amygdala and cortical areas we conducted PPI analyses using an automated generalized toolbox (gPPI; McLaren, 2012), which allows for simultaneous modeling of context-dependent connectivity for all included conditions (McLaren, 2012). For two separately conducted gPPIs, functionally defined ROIs of the left and right amygdala, originated from the WatchNeg > WatchNeu group-contrast, were used as seed regions. Only those participants who showed at least one activated voxel during WatchNeg > RegulateNeg at a threshold of  $T = 0.05$  were included (Supplementary Materials). From the ROIs the first eigenvariate of the individual voxel time-series was extracted and multiplied with all psychological vectors previously included in the GLM. To compare effects between task conditions, RegulateNeg > WatchNeg PPI contrasts were computed at the subject-level and then taken to group-level t-tests. As we aimed to test functional connectivity dependent on the level of self-control, we included the self-control score as a covariate of interest in the second level analysis. Results regarding this covariate were examined on the whole brain level ( $P < 0.001$ , FWE-cluster-corrected at  $P < 0.05$ ).

## Results

### Subjective ratings

Mean ratings ( $\pm$  SE) of the strength of negative feelings were calculated per condition (Figure 1b). An ANOVA revealed a significant difference in negative feelings dependent on the task condition,  $F(2, 214) = 458.03$ ,  $P < 0.001$ ,  $\eta^2 = 0.81$ . When compared with neutral pictures ( $m = 2.68 \pm 0.11$ ), negative pictures induced stronger negative feelings during the WatchNeg condition ( $m = 6.53 \pm 0.11$ ),  $t(107) = -39.98$ ,  $P < 0.001$ , and the RegulateNeg condition ( $m = 4.36 \pm 0.13$ ),  $t(107) = -12.36$ ,  $P < 0.001$ . On RegulateNeg-trials, negative feelings were less intense than after WatchNeg,  $t(107) = 18.46$ ,  $P < 0.001$ , indicating a successful down-regulation of negative emotions.

### Self-control questionnaires and relation to subjective ratings

Means, SDs, reliability coefficients and inter-correlations of the self-report questionnaires are shown in Table 1. As expected, the questionnaires were highly correlated. The factor analysis revealed one component with an Eigenvalue of 2.099 explaining 69.96% of the variance, termed 'Self-Control' (for further components below the extraction criteria of Eigenvalue > 1 see

Supplementary Materials 'Results' section). This value was used as a measure of self-control.

There was a positive correlation between this self-control score and the difference in ratings between WatchNeg > RegulateNeg (Figure 2), indicating that high self-controllers indeed regulated their emotions more successfully. Separated correlation analyses between each scale and the subjective regulation success are provided in the supplementary Material Section 1.2.1.

To test whether IQ, self-efficacy or effort mediated the positive relation between emotion regulation success and self-control Pearson Correlations were calculated. Results showed that none of these variables correlated significantly with both emotion regulation success and self-control ( $P \gg 0.05$ ; for detailed analyses see Supplementary Materials), indicating that IQ, self-efficacy and effort did not act as mediators. Therefore we did not include these variables in further analyses.

### Brain activation

As expected, the whole-brain analysis of the RegulateNeg > WatchNeg contrast showed increased activation in lateral parts of the PFC, such as the left and right middle (MFG), inferior (IFG) and superior frontal gyrus ( $P < 0.05$ , FWE-corrected; Figure 3a). Similarly, medial areas like the midcingulate cortex and superior medial gyrus were activated, as well as the IPL. Together these areas represent the regulation-network (Supplementary Table S5).

Within the amygdala ROIs, there was increased activity during WatchNeg > RegulateNeg (i.e. the neural down-regulation effect when looked at inversely) in the right ( $t_{\max} = 4.86$ ,  $k = 41$ , MNI peak coordinates (PCs) = 27 -1 -20) and left amygdala

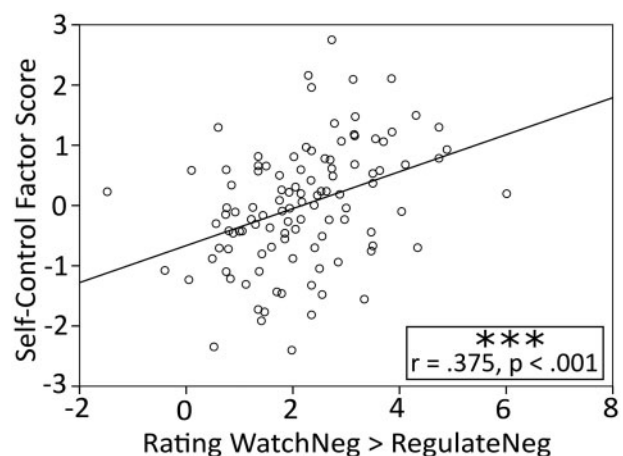


Fig. 2. Self-control and regulation success. Higher scores of self-control are correlated with greater regulation success, indicated by less intense negative feelings during RegulateNeg compared with WatchNeg trials. \*\*\* $P < 0.001$ .

Table 1. Descriptives and Pearson's Correlation between Self-Control Reports

	Descriptives					Correlations		
	Min	Max	Mean	SD	Cronbach's $\alpha$	1.	2.	3.
1. BSCS	21	60	39.33	7.84	0.840	1		
2. SRS	17	38	28.57	4.55	0.852	0.608***	1	
3. BIS-11	42	89	63.84	10.02	0.823	-0.533***	-0.506***	1

BSCS, Brief Self Control Scale; SRS, Self-Regulation Scale; BIS, Barratt Impulsiveness Scale; SD, standard deviation; \*\*\* $P < 0.001$ ,  $n = 108$ .

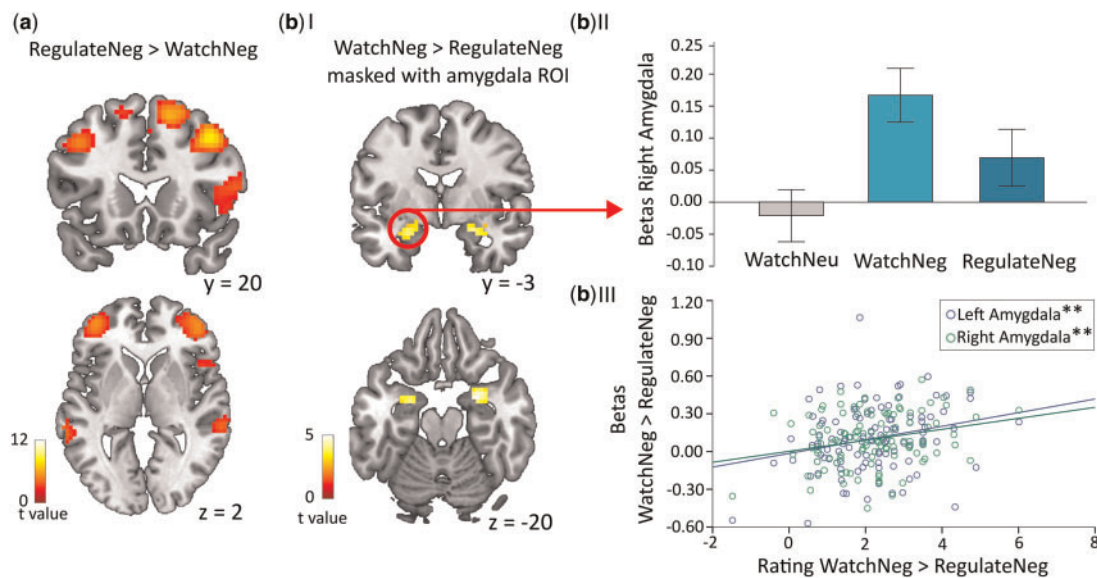


Fig. 3. fMRI results. (a) There was increased activation during RegulateNeg in prefrontal and parietal areas ( $n = 108$ ,  $P < 0.05$ , whole-brain FWE-corrected). (b.I) In the amygdala ROIs, there was higher activation for WatchNeg ( $P < 0.05$ , FWE-SVC). (b.II) Extracted betas of the right amygdala (b.III). The lower the amygdala activation during RegulateNeg compared with WatchNeg-trials, the greater was the regulation success, indicated by subjective ratings. \*\* $P < 0.01$ .

( $t_{\max} = 4.15$ ,  $k = 25$ , MNI PCs =  $-24 -4 -20$ ) at  $P < 0.05$ , FWE-SVC (Figure 3b (I)). The extracted betas of the activated cluster showed the same pattern as the subjective rating, with amygdala activity lowest in WatchNeu-, highest in WatchNeg-, and medium in RegulateNeg-trials (Figure 3b (II)).

To examine whether the activation difference during WatchNeg- and RegulateNeg-trials was correlated with the strength of the experienced negative feelings after WatchNeg-compared with RegulateNeg-trials, we calculated Pearson's correlation coefficient of the two differences. The resulting positive correlation (Figure 3b (III)) between the WatchNeg > RegulateNeg rating differences and the betas from the right,  $r = 0.255$ ,  $P = 0.008$ , and the left,  $r = 0.254$ ,  $P = 0.008$ , amygdala, indicated that regulation success was associated with stronger down-regulation of the amygdala.

#### Association between self-control and brain activation

**Overall activation.** In contrast to our hypothesis, there was no stronger activation during RegulateNeg > WatchNeg in the task-related network when self-control was included as a covariate. Only when disregarding the cluster threshold, an activated region in the right superior parietal cortex was visible (MNI PCs:  $18 -73 49$ ,  $k = 3$ ,  $T = 3.50$ ,  $P < 0.001$ , uncorrected on peak level). Vice versa, the extracted betas from the amygdala cluster (Figure 3b (I)) also showed no correlation between amygdala down-regulation during RegulateNeg > WatchNeg and the self-control factor ( $P > 0.05$ ). Testing whether the general emotional reactivity to negative stimuli was related to self-control resulted in no significant correlation between amygdala activity during WatchNeg > WatchNeutral and the self-control factor (for detailed analysis see Supplementary Materials).

**Amygdala activity over time.** Since we did not find a correlation between self-control and overall activation of the regulation network or of amygdala down-regulation, we tested one additional hypothesis: higher self-control might also be related to the perseverance of successful amygdala down-regulation over time. To examine this, we assessed whether amygdala activity

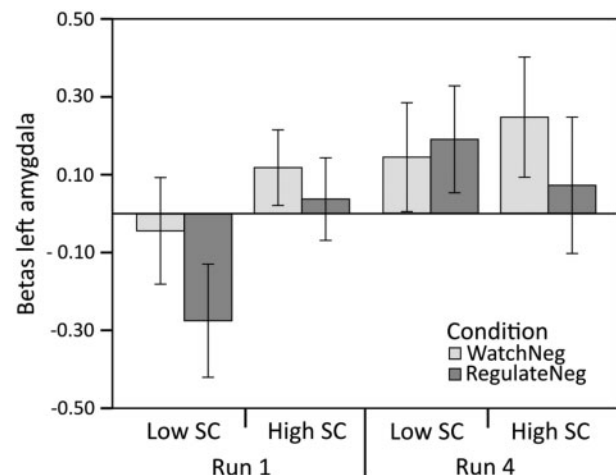


Fig. 4. Amygdala activation over time. Individuals with high self-control were more successful in maintaining the down-regulation of the amygdala over time. When dividing the participants into three equal groups with the lower tertile classified as the LSC group, and the upper tertile as the HSCs group, the graph visualizes that in Run 4 HSCs successfully down-regulated the amygdala activity in RegulateNeg- compared with WatchNeg-trials, while LSCs did not.

during the first and last run was down-regulated differently depending on the level of self-control (Figure 4).

In a first step, we calculated the amygdala down-regulation (WatchNeg > RegulateNeg) per run. Next we determined the difference of down-regulation between the first and the fourth run (Run1 > Run4). The resulting value reflected whether amygdala down-regulation was executed similarly successful in both runs (smaller value) or became worse over time (greater value).

Correlating left amygdala down-regulation over time with the self-control factor score showed that lower self-control is associated with less amygdala down-regulation in Run 4 compared with Run 1 ( $r = -0.216$ ,  $P = 0.025$ ). This indicates that individuals with greater strength of self-control are more successful in maintaining the regulation of brain activity associated with

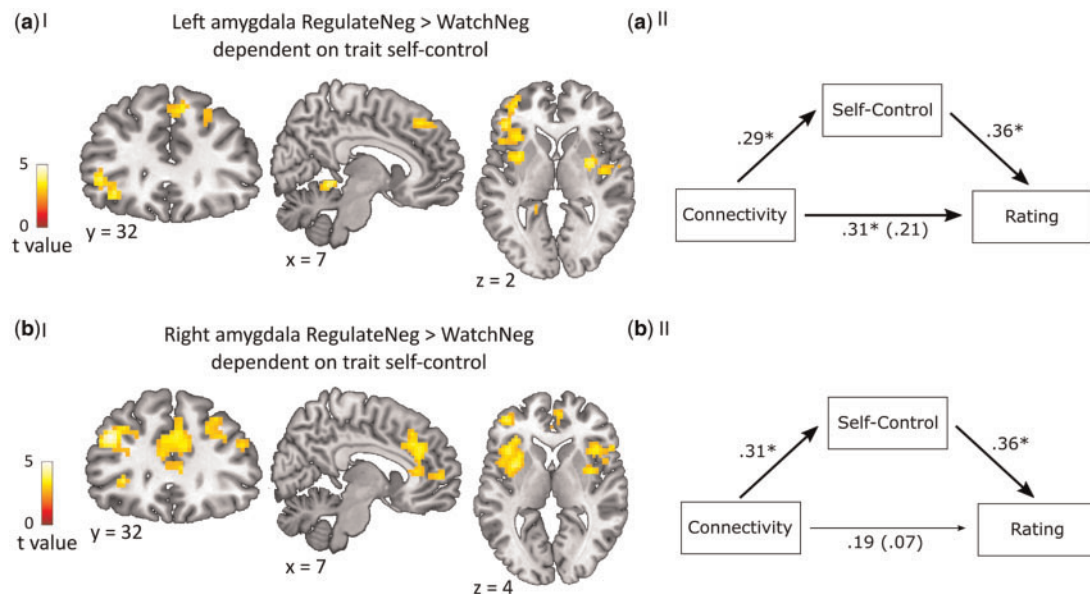


Fig. 5. PPI results. Higher self-control scores correlated with stronger functional connectivity between the (a.I.) left and (b.I.) right amygdala and medial and lateral prefrontal areas during RegulateNeg compared with WatchNeg ( $P < 0.001$ , FWE cluster corrected at  $P < 0.05$ ). In the (a.II.) left but not (b.II.) right amygdala stronger amygdala-PFC connectivity correlated with emotion regulation success (Rating). This effect was mediated by self-control, as indicated by the non-significant regression coefficient (in parentheses) when controlling for self-control. \* $P \leq 0.05$ .

negative emotions over time. This association of self-control and amygdala down-regulation over time is illustrated in Figure 4. Here, we exemplified amygdala activation per run and condition separately for individuals with high and low levels of self-control. For this purpose, participants were divided into three equal groups with the lower tertile classified as the low self-control group (LSC; score  $< -0.423$ ,  $n = 36$ ), and the upper tertile as the high self-control group (HSC; score  $> 0.496$ ,  $n = 36$ ). The graph visualizes that in Run 4 HSCs successfully down-regulated the amygdala activity in RegulateNeg- compared with WatchNeg-trials, while LSCs did not.

This effect was specific to the left amygdala—the activity of the right amygdala did not show a significant relationship between down-regulation over time and self-control score ( $r = -0.015$ ,  $P = 0.877$ ).

### Association between self-control and functional connectivity

Next, we tested whether stronger self-control was associated with greater functional connectivity between the amygdala and PFC areas which might be involved in emotion regulation. The PPI analysis revealed that trait self-control was related to higher functional connectivity for RegulateNeg > WatchNeg between the left (Figure 5a (I)) and right (Figure 5b (I)) amygdala and areas in the lateral and medial PFC, such as the MFG, IFG and anterior cingulate cortex, as well as the insula. Regarding the left amygdala, further peak activations were located in parietal regions, such as the IPL and precuneus, but also the cerebellum and temporal cortex (Supplementary Tables S6 and S7).

To test whether this functional connectivity was associated with greater regulation success, we extracted the betas of all voxels within the network identified by the PPI analysis. Using these betas, the mean functional connectivity strength for the right and left amygdala was calculated per participant and correlated with the ratings. As shown in Figure 5, increased overall functional connectivity of the left,  $r = 0.305$ ,  $P = 0.004$ , but not

right,  $r = 0.187$ ,  $P = 0.075$ , amygdala was associated with lower intensity of negative feelings after RegulateNeg- compared with WatchNeg-trials. Next, we tested whether this association between connectivity and rating was mediated by self-control. As illustrated in Figure 5a (II), when controlling for self-control the indirect effect of connectivity on the rating was lessened to  $r = 0.21$ . To test the significance of this indirect effect we used bootstrapping procedures by computing 1000 bootstrap samples. A 95% bias-corrected confidence interval was calculated using the 2.5th and 97.5th percentiles of bootstrap distributions. The bootstrapped indirect effect was 0.71, with the 95% confidence interval ranging from 0.29 to 1.28, indicating a significant effect. To verify this result we finally conducted the Sobel-test,  $Z = 0.71$ ,  $P = 0.031$ ,  $\kappa^2 = 0.11$ , which was also significant. Altogether these tests support the assumption that there is a relation between the strength of connectivity and successful emotion regulation, but self-control mediates this association at least partially.

### Discussion

Here, we investigated whether emotion regulation abilities are associated with trait self-control. For this purpose, we used an emotion regulation task in which participants were instructed to permit or down-regulate their emotions by distancing from a negative scene and to indicate the intensity of experienced negative feelings after each trial. Our analyses revealed that stronger self-reported self-control is associated with more successful emotion regulation, indicated by subjective ratings. Furthermore, high self-controllers showed higher functional connectivity of the right and left amygdala with several PFC regions during regulating as compared with permitting negative emotions. For the left amygdala, this increased functional connectivity with the PFC was associated with greater success in emotion regulation as indicated by the ratings. Comparing the first and the last run of the experiment showed that HSCs successfully maintained left amygdala down-regulation over time,



while LSCs failed to down-regulate towards the end of the experiment.

Together these findings indicate that individuals with high self-control are characterized by higher amygdala-PFC functional connectivity during emotion regulation which might enable them to (i) down-regulate their negative emotions more successfully in general, and (ii) maintain this regulation over time.

## General emotion regulation effects

Our results concerning the association of subjective ratings and fMRI activity changes during emotion regulation are consistent with previous findings, which is an important prerequisite for relating them to self-control: Subjective ratings indicated reduced negative feelings during RegulateNeg > WatchNeg (Gross, 1998a; Ochsner et al., 2004; McRae et al., 2010) and the amygdala was less activated during emotion regulation (Walter et al., 2009; Kanske et al., 2010; Schardt et al., 2010). This supports the idea that amygdala activity reflects the process of distancing (Walter et al., 2009; Erk et al., 2010a; Gaebler et al., 2014; Lamke et al., 2014). In line with this, the activation difference between RegulateNeg and WatchNeg correlated with the decline of experienced negative feelings after distancing (Ochsner et al., 2004). This suggests that the amygdala activity was directly associated with the experience/processing of negative feelings, and that participants successfully used distancing as a regulation strategy. Emotion regulation was additionally associated with greater activation in an extended network, including the bilateral MFG, superior frontal gyrus, mPFC, IPL and middle temporal as well as the right IFG. Most of these regions are assumed to play a role in diverse forms of self-control and cognitive control (Miller and Cohen, 2001) and have previously been reported to be involved in emotion regulation, especially in distancing (Dörfel et al., 2014).

## Trait self-control and emotion regulation

This study showed that high self-controllers are more successful in regulating their emotions, as indicated by subjective ratings. Previous studies already suggested that self-control is associated with greater emotional stability (Daly et al., 2014; Tangney et al., 2004) and that this emotional stability can even be increased after a self-control training (Oaten and Cheng, 2006). To measure emotion regulation, these authors used short questionnaires assessing how often in daily life individuals experienced negative emotions. In contrast, the present study provides an experimental measure for individual emotion regulation ability derived from an emotion regulation task, which circumvents problems such as response biases associated with self-reported emotion-related questionnaires.

Importantly, Duckworth and Kern (2011) showed that tasks measuring executive functioning and delay of gratification were only weakly correlated to self-reported self-control (all  $r$ s between 0.11 and 0.21). The correlation between emotion regulation success and the self-control score was considerably higher ( $r = 0.375$ ) in the present study. This might indicate that emotion regulation ability is more strongly associated with trait self-control (as measured by current questionnaire measures) than executive functioning and delay of gratification.

## Cognitive control and self-control

One potential explanation for the observed effects relies on the fact that distancing is a highly cognitive regulation strategy: After the emotional information of a stimulus is perceived, the perspective from which the stimulus is experienced has to be manipulated (Ochsner et al., 2004). This process might involve the cognitive inhibition of pre-potent appraisals, the cognitive shift of attention away from the perceived stimulus towards the self, and also the cognitive maintenance of the intention to detach (Staudinger et al., 2009; Dörfel et al., 2014). Thus, cognitive control mechanisms might sub-serve successful emotion regulation. At the same time overlapping cognitive functions might mediate successful self-control.

Evidence for an association of self-control and cognitive control functions comes from studies showing that self-control can be temporally impaired by high cognitive load (Ward and Mann, 2000), or preceding exhausting cognitive tasks (Hagger et al., 2010). Specific types of cognitive functions, such as working memory, are supposed to support self-regulation (Hofmann et al., 2012). More effective attentional focusing and distractor resistance might enable individuals with high working memory to elicit less automatic, impulse-driven and more goal-oriented reactions (Barrett et al., 2004; Friese et al., 2008), both leading to more successful goal achievement.

Similar, individuals with less effective behavioral inhibition in a cognitive task showed more problems related to low impulse control, such as weight gain (Nederkorn et al., 2010) or smoking (Berkman et al., 2011). Conversely, Providing training to improve behavioral inhibition supported the reduction of alcohol consumption in problematic drinkers (Houben et al., 2011). Thus, assuming that cognitive control skills support the mechanisms, which are important in pursuing goals, high self-controllers might be more successful in applying reappraisal as a cognitive regulation strategy and therefore experience reduced negative emotions.

## Functional connectivity

Following the assumption that high self-controllers show greater emotion regulation success due to higher cognitive control, one might expect a correlation between the recruitment of cognitive resources and the strength of self-control. Similar to findings of Wagner et al. (2013), we did not find trait control related differences in the 'activation' of the regulation-related network or the 'down-regulation' of the amygdala. Instead, we observed that dependent on trait self-control, the amygdala showed stronger functional 'connectivity' to cognitive-control-related PFC and parietal regions. Parts of these regions overlapped with the regulation-related network, like the MFG, IFG, mPFC and IPL, as observed in previous functional connectivity studies of distancing (Erk et al., 2010a; Schardt et al., 2010). On the one hand, this lack of a significant relation of self-control and PFC activity might be based on the fact that our participants were all relatively high in trait self-control. This restricted variance of the self-control score might have reduced the power of the correlations. On the other hand, this observation is in so far interesting, as it contradicts the assumption of a simple dual process account. Finding that not the activity in one specific PFC region, but the amygdala-PFC connectivity is related to the strength of self-control might be indicative for a more complex account. Considering studies about cognitive control, the PFC regions observed in this study may be involved in the reappraisal of emotions by an interplay of specific functions



(Ochsner and Gross, 2005): Lateral parts like the MFG and IFG might keep a representation of the task (D'Esposito et al., 1999) and be responsible for the actual task implementation by inhibiting prepotent appraisals (Chikazoe, 2010), respectively. The mPFC might play a role in comparing changing of the inner emotional state, while the IPL, which has been shown to be exclusively activated in distancing compared with other strategies of emotion regulation (Dörfel et al., 2014), might be crucial for multisensory integration of self-other-related information (Silani et al., 2013).

Thus, stronger functional connectivity between these regions and the amygdala in HSCs might indicate that these individuals are more effective in recruiting/exerting cognitive control to down-regulate their emotions by distancing. This would explain why they experienced reduced negative feelings compared with LSCs. Further studies are required here to investigate the specificity of changes in amygdala connectivity and the modulation of negative feeling.

Alternatively, based on previous studies one might have expected that the vmPFC plays a special role when investigating successful emotion regulation dependent on self-control. On the one hand, the vmPFC is assumed to be involved in self-control-related valuation processes (e.g. Hare et al., 2009). On the other hand the vmPFC has also been observed to show stronger connectivity with the amygdala during emotion regulation (e.g. Banks et al., 2007; Johnstone et al., 2007; Delgado et al., 2008). Based on sparse anatomical connections between the lateral PFC and the amygdala (Ghashghaei et al., 2007), it has been suggested that the vmPFC might act as an interstation between cognitive control regions and amygdala (Urry et al., 2006; Etkin et al., 2011). Following this, in our study the vmPFC might have been expected to serve as an interface between the appraisals of emotional events by modulating the amygdala and the strength of applied self-control by valuating individual goals. In contrast to other studies which found amygdala-vmPFC connectivity to be related to individual differences (Urry et al., 2006; Johnstone et al., 2007; Schardt et al., 2010), we did not observe a relation between the strength of self-control and vmPFC activity or amygdala-vmPFC connectivity during emotion regulation.

Generally, the literature is divided when it comes to vmPFC involvement in reappraisal. In contrast to a meta-analysis by Diekhof et al. (2011) a more recent one by Buhle et al. (2013) did not observe the vmPFC to be consistently activated during cognitive reappraisal. Also in this study, we did not observe the vmPFC to be involved in emotion regulation *per se*. This might be related to the specific regulation strategy. Directly comparing four different emotion regulation strategies indicated that dorsomedial but not ventromedial areas of the PFC are involved in distancing (Dörfel et al., 2014). However, there are also studies which found the vmPFC to be activated during distancing (Ochsner et al., 2004). From our results we can only speculate that even if valuation processes in the vmPFC are involved in distancing, the strength of self-control does not affect them. Rather our data suggest that stronger self-control is related to greater engagement of cognitive resources in terms of stronger connectivity of the amygdala with other medial and lateral PFC regions. This would also be in line with the theory proposed by McClure et al. (2004, 2007), stating that the vmPFC is part of a valuation network which is activated when immediate rewards are involved, while the lateral PFC is involved in the exertion of control in favor of long-term goals. Equivalent to the self-control-related modulatory relationship between the DLPFC and vmPFC in decision making (Hare et al., 2009), in emotion

regulation PFC regions might have modulatory effects on the amygdala according to the current individual long-term goal.

### Amygdala down-regulation over time

In our study, high and low self-controllers differed in terms of amygdala down-regulation over time. Although HSCs showed similar amygdala down-regulation throughout the experiment, LSCs failed in down-regulation towards the end. This might be due to the fact that exerting self-control is an exhausting process and might lead to a gradual decline in self-control performance (e.g. Baumeister, 1998). These effects might occur only in LSCs because self-control might be a limited resource (Baumeister, 1998; but see Carter and McCullough, 2014) and HSCs might have access to greater resources. However, as these depletion effects can be diminished, for instance by paying performance-dependent sufficient incentives (Muraven and Slessareva, 2003) or personal engagement in the task (Hockey and Earle, 2006), motivation might be an additional crucial factor that mediates these effects. For instance, opportunity-cost models assume that a cost-benefit analysis between the mental effort and the current task goal is computed and competes with costs and values of alternative actions (Hockey, 2011; Kurzban et al., 2013). The process-model account by Inzlicht et al. (2014) further suggests that this priority-selection depends on how much self-control has recently been executed and also allows for adjustments according to other factors like performance feedback. Although in our study initially all participants might have been motivated to engage cognitive effort in favor of avoiding the experience of negative emotions (e.g. to increase well-being, Arthaud-day et al., 2005; or to reduce stress, Feldman et al., 1999) or another task-related overarching goal (e.g. pleasing the experimenter; demonstrating competence, Ryan and Deci, 2000; gratifying curiosity, Kashdan et al., 2004), HSCs might have remained longer in a motivated state that supports pursuing these goals. Conversely, LSCs might have switched earlier to a motivational state that favored other personal goals over task-related goals. The observed greater functional connectivity in HSCs may reflect this difference in task engagement and reflect a more effective and enduring application of cognitive control.

### Limitations

Importantly, we point out that the association between self-control and emotion regulation is of correlational nature and does not provide information about whether it is a direct or indirect relation. Analyzing several variables, which are generally related to controlled behavior indicated that IQ, self-efficacy beliefs or effort did not mediate the observed relation between self-control and emotion regulation (Supplementary Materials). However, of course there might be many other factors which influence controlled behavior but we did not assess in our study (e.g. childhood SES in self-control: Moffitt et al. (2011); and emotion regulation: Eisenberg et al., 1993). Therefore, our results provide a proper basis for further investigations, investigating the exact relation between self-control and emotion regulation.

Further, our approach to define the amygdala as a seed region for the PPI analysis restricts our findings to networks or mechanism which assume that the down-regulation of the amygdala is necessarily involved when down-regulating negative emotions. As set up in the introduction, we defined this criterion based on evidences from previous studies. However, for instance very low self-controlled individuals might involve

other networks in emotion regulation compared with relatively high self-controlled individuals. Using multidimensional connectivity procedures in future studies might allow for investigating alternative networks, which are not directly or not only related to amygdala down-regulation.

## Conclusion

In sum, our results expand previous studies indicating that state self-control is associated with emotion regulation abilities (Wagner and Heatherton, 2013), by showing that trait self-control is directly related to successful down-regulation of negative emotions. The finding that these differences are based on variations in functional connectivity demonstrates the importance of considering network analysis to investigate personality related effects on the neural level and might provide research approaches for future investigations in this field.

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## Supplementary data

Supplementary data are available at SCAN online.

Conflict of interest. None declared.

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