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Cognitive reward control recruits medial and lateral frontal cortices, which are also involved in cognitive emotion regulation: A coordinate-based meta-analysis of fMRI studies

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ABSTRACT

Cognitive reward control (CRC) refers to the cognitive control of one's craving for hedonic stimuli, like food, sex, or drugs. Numerous functional magnetic resonance imaging (fMRI) studies have investigated neural sources of CRC. However, a consistent pattern of brain activation across stimulus types has not been identified so far. We addressed this question using coordinate-based meta-analysis of task-fMRI studies during CRC. To further characterize such a potential common CRC activation pattern, we extended our approach to three additional questions: (i) Do CRC meta-analytic results overlap with those during the control of emotional states, such as in cognitive regulation of aversive emotions (cognitive emotion regulation, CER)? (ii) How does the control of motivational/emotional states link to the control of action states with less motivational/emotional valence such as in response inhibition paradigms, i.e., do meta-anyltic result maps overlap? (iii) Does the control of motivational/emotional states constitute a consistent pattern of organized (i.e., coherent) ongoing or intrinsic brain activity? This question was tested by a seed-based intrinsic functional connectivity (iFC) analysis in an independent data set of resting-state fMRI.

We found consistent CRC activation mainly in supplementary motor, dorsolateral prefrontal, and ventrolateral prefrontal cortices across studies. This activation pattern overlapped largely with CER-related activation, except for left-sided lateral temporal and parietal cortex activation, which was more pronounced during CER. It overlapped partly with activation during response inhibition in (pre-)supplementary motor, insular, and parietal cortices, but differed from it in dorsolateral and ventrolateral prefrontal cortices. Furthermore, it remarkably defined an iFC network covering activation patterns of both CRC and CER.

Results demonstrate a consistent activation pattern of CRC across stimulus types, which overlaps largely with those of CER but only partly with those of response inhibition and constitutes an intrinsic co-activity network. These data suggest a common mechanism for the cognitive control of both motivational and emotional stimuli.

1. Introduction

When you return from work in a hungry state, you can decide between eating vegetables or a chocolate cake. The chocolate cake would quickly allay your hunger. However, thinking about long-term health consequences or societal weight norms might make you reconsider your choice. In this way, you may overcome the craving towards the cake and instead select the vegetables. Such dietary reward control is a specific instance of 'cognitive reward control' (CRC), which refers to the cognitive regulation of one's craving towards a rewarding stimulus (Kelley et al., 2015). A recent meta-analysis has shown consistent brain activation in this specific type of CRC across insular, prefrontal, and parietal cortices (Han et al., 2018). However, CRC is applied to a wide range of motivational stimuli, from food to sex and drugs (Brody et al., 2007; Crockett et al., 2013; Kober et al., 2010). Although several functional magnetic resonance imaging (fMRI) studies have investigated task

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activation patterns during CRC via changes in blood oxygenation (Brody et al., 2007; Crockett et al., 2013; Kober et al., 2010), due to heterogeneous methods and results no consistent pattern across stimulus types has been identified so far. Therefore, it is unclear whether the activation pattern of dietary reward control generalizes also for other stimulus types. The suggestion that there should be a common CRC network is supported by theories of model-based decision-making, which covers CRC. In such theories, decision-making, i.e., the selection of behavior, ranges on a spectrum from model-free decisions (i.e., decisions are driven by previous experience/prediction errors; also called habitual or retrospective behavior selection) to model-based decisions (i.e., employing cognitive models of subject-environment interactions; also called goal-directed or prospective behavior selection) (Daw et al., 2005; Dolan and Dayan, 2013). In particular, model-based decision making, which might underpin CRC, is typically supported by activation in dorsolateral and ventrolateral prefrontal as well as supplementary motor and dorsomedial prefrontal cortices (Etkin et al., 2015; Kelley et al., 2015). This conceptualization suggests that these regions' activation might underlie CRC across distinct stimulus types.

In order to detect consistent neural correlates across CRC studies with different methodological implementations, meta-analysis is a powerful tool. Therefore, we conducted coordinate-based meta-analysis of task-fMRI studies in CRC across stimulus types to address the question of a common CRC activation network. In this way, this analysis of common CRC extends previous analyses of dietary CRC (Han et al., 2018). We included all fMRI studies using tasks in which subjects cognitively controlled hedonic impulses towards rewarding cues (e.g., food, sex, cigarettes, money) and synthesized results using Multilevel Kernel Density Analysis (MKDA) (Wager et al., 2007). We hypothesized consistent activation in ventrolateral (vlPFC) and dorsolateral (dlPFC) prefrontal, parietal, and (pre-)supplementary motor areas (pre-SMA, SMA) (Etkin et al., 2015; Kelley et al., 2015).

In order to further characterize such a potential common CRC activation pattern, we extended our approach to three additional questions: (i) How does the control of motivational states by CRC link to the control of emotional states, such as cognitive regulation of aversive emotions; (ii) How does the control of motivational/emotional states link to the control of action states with less motivational/emotional valence, such as the ones typically defined by response inhibition paradigms; (iii) Does the control of motivational/emotional states constitute a consistent pattern of organized (i.e., coherent) ongoing or intrinsic brain activity, which is distinct from but related with task-activation conditions.

Ad (i) Motivational and emotional control. Apart from cognitively controlling craving towards rewarding stimuli, one can also control emotional responses towards aversive stimuli. For example, seeing a snake usually triggers a fearful reaction. However, when a snake is behind the glass of a terrarium, one might be able to downregulate that response. Such cognitive emotion regulation (CER) has been described as another example of model-based decision-making (Etkin et al., 2015). CER refers to strategies that cognitively modulate emotional states (Braunstein et al., 2017; Gross, 2002; Gross and Barrett, 2011), and it has been assumed that during CER, an internal model is applied to select the appropriate emotion-regulatory action for achieving a desired emotional state. Thus, the underlying computational models and related neural mechanisms of aversive CER might resemble those of reward-related model-based decision-making, such as CRC: both model-based control strategies involve decisions about actions, which alter either one's emotional state or one's craving towards consumption of a rewarding stimulus. Keeping this question at a neurobiological level, this theory suggests that neural correlates of CER should resemble neural correlates of CRC, indicating similar generating neural mechanisms. Previous coordinate-based meta-analyses of CER support this idea, showing consistent brain activation in dlPFC, vlPFC, SMA, pre-SMA, temporal, and parietal cortices (Buhle et al., 2014; Diekhof et al., 2011; Frank et al., 2014; Kalisch, 2009; Kohn et al., 2014; Langner et al., 2018; Morawetz et al., 2017b).

We tested this hypothesis by complementing the CRC meta-analysis with a coordinate-based meta-analysis of task-fMRI studies in CER, i.e., studies in which subjects cognitively down-regulated negative emotional responses elicited by aversive pictures via reappraisal (Goldin et al., 2008; Gross, 2002; Ochsner et al., 2002). Then we tested for common and distinct activation patterns across CRC and CER via meta-analytic contrast and conjunction (Radua et al., 2013). We expected common activation in vlPFC, dlPFC, SMA, pre-SMA, and parietal cortices (Etkin et al., 2015). Of note, this approach contrasts with a recent meta-analysis by Langner and colleagues, which reported common and distinct neural correlates for the cognitive control of emotion and action (Langner et al., 2018). As their framework of "cognitive action control" did not comprise CRC, they included different task paradigms.

Ad (ii) Motivational/emotional control and response control. To foreshadow our findings, we observed a large overlap of CRC and CER activation patterns, suggesting a common mechanism for the control of motivational and emotional states. In order to investigate whether our results of common control are specific to CRC and CER or rather reflect a general pattern of cognitive control of states/responses to stimuli with and without affective valence, we analyzed brain activations during the control of actions with less affective valence than those of motivational and emotional states of CRC and CER. Specifically, we performed a further meta-analysis of studies of response inhibition, in which actions in response to certain stimuli are suppressed or inhibited (Langner et al., 2018). For this control meta-analysis, we selected all fMRI studies employing either a Go/NoGo or Stop signal task in healthy subjects, and compared activation patterns with those of CRC and CER.

Ad (iii) Motivational/emotional control as a network of coherent ongoing activity. Finally, we investigated whether the common CRC/CER activation pattern defines an intrinsic, permanently present co-activity network of coherent ongoing activity. This analysis was driven by ideas that self-regulation in general (i.e., across different functional domains including CRC and CER, but also top-down cognitive control etc. (Cole et al., 2014; Kelley et al., 2015; Lindquist and Barrett, 2012; Power et al., 2011)) reflects ongoing brain processes. These processes - apart from event-related activations - are already present in the intrinsic architecture of brain activity, reflecting previous self-regulatory performances on the one hand and shaping future ones on the other hand. This specific idea partly reflects the more general notion that the organization of ongoing brain activity – typically measured during resting state – is shaped by previous and shapes future cognitive task activations (Berkes et al., 2011; Cole et al., 2016; Rosenberg et al., 2016; Smith et al., 2009; Tavor et al., 2016). Concretely, Kelley and colleagues proposed domain-general intrinsic brain networks to underlie successful self-regulation; candidates for such domain-general control networks might be fronto-parietal and cingulo-opercular task-control networks, default-mode network, and ventral attention network (Kelley et al., 2015; Power et al., 2011). A way to establish such networks is intrinsic functional connectivity (iFC) of slowly fluctuating ongoing brain activity (Biswal et al., 1995), which organizes brain activity and can be investigated by coherent spontaneous fluctuations of blood-oxygenation measured by resting-state functional MRI (rs-fMRI) (Buckner et al., 2013; Fox and Raichle, 2007; Mateo et al., 2017; Raichle, 2011).

To address the question whether a common CRC/CER activation pattern defines a permanently present intrinsic co-activity network, we complemented the meta-analyses by a seed-based iFC-analysis. We used rs-fMRI data from an independent dataset of 80 healthy subjects and defined the common CRC/CER activation pattern (output of meta-analytic conjunction analysis) as seed to identify a CRC/CER iFC-network.

2. Material and methods

2.1. CRC: coordinate-based meta-analysis

2.1.1. Literature search

PubMed and Web of Science were searched until 18/04/2018 using the keywords *(self-regulat* OR impulse control OR self-control OR restrain) AND (fMRI OR neuroimaging)* (Fig. 1A). Additional relevant studies were identified using reviews and reference lists.

CRC is usually studied by instructing subjects to control their craving towards rewarding stimuli (e.g., food, money, or sex), whose consumption is not compatible with internal long-term goals or societal norms. For example, when feeling the impulse of eating a chocolate dessert, an internal model of long-term health consequences may inhibit this impulse (Hare et al., 2011). Thus, the experiment design in the selected CRC studies contrasted two conditions: "*Reward baseline*", in which subjects were asked to allow themselves to crave a desirable reward cue they were viewing, e.g., cigarettes or tasty food, and "*CRC*", in which participants should resist any desirable reward by, for example, thinking about long-term consequences of repeatedly consuming the substance (Brody et al., 2007; Crockett et al., 2013; Kober et al., 2010). We only included studies using visual stimuli such as pictures and videos (Buhle et al., 2014; Kohn et al., 2014). Furthermore, only studies in which subjects were instructed to down-regulate their hedonic impulses towards reinforcing cues (e.g., tasty food or erotic pictures) were considered; studies with a different goal like up-regulation were not included.

Further exclusion criteria were: (i) use of subjects with mental disorders, (ii) no whole-brain analysis (restriction to predefined regions of interest), (iii) no report of coordinates in MNI or Talairach space.

2.1.2. Data extraction

Peak coordinates of activation differences between the two conditions (CRC vs. Reward baseline) were extracted from the studies and converted to MNI space if necessary.

2.1.3. Meta-analysis

For coordinate-based meta-analysis, we used Multilevel Kernel Density Analysis (MKDA) (Etkin and Wager, 2007; Wager et al., 2007), which comprises the following steps: first, peak coordinates of each study contrast map were convolved separately with a spherical kernel (radius = 15 mm) to create so-called comparison indicator maps. In these indicator maps, each voxel had either the intensity value 1 (= at least one peak within 15 mm of this voxel) or 0 (= no peak within 15 mm of this voxel). Subsequently, indicator maps were weighted by sample size and averaged across studies to yield so-called density maps, showing the weighted proportion of contrast maps that report a peak within 15 mm of each voxel (=density statistic). In this step, the hypoactivation map was subtracted from the hyperactivation map in order to identify brain regions which are specifically hyperactivated, but not hypoactivated during CRC.

Due to our hypothesis, we only investigated the meta-analytic contrast "CRC > Reward baseline".

To test for statistical significance of meta-analytic result clusters in the density maps, a Monte Carlo simulation with 15,000 iterations was performed to establish a family-wise error rate (FWER) threshold. Significant result clusters were detected for $p < 0.05$ (FWER-corrected), both based on voxel-wise density statistic (height-based threshold) and cluster size (extent-based threshold) (Wager et al., 2007). Both thresholds were reported since they provide complementary information (Kaiser et al., 2015). To control for potential confounding effects (such as disproportionate influence of a single study) on our meta-analytic results, we performed several post-hoc control analyses which are presented in detail below after the description of the CER meta-analysis.

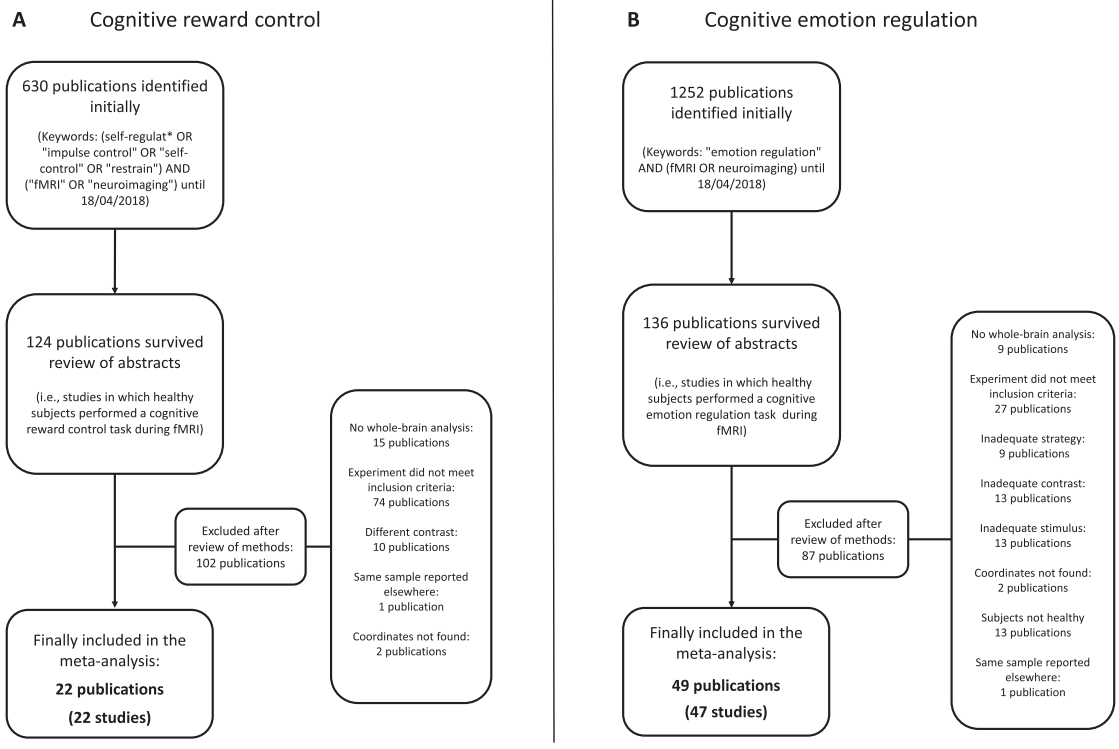

Fig. 1. Flow diagram of literature search.
Literature search for cognitive reward control (A), yielding a total of 22 publications (22 studies) and 741 subjects, and for cognitive emotion regulation (B), yielding a total of 49 publications (47 studies) and 1455 subjects. Keywords and exclusion criteria are indicated. Publications using identical subject samples were counted as one single study; thus, there were less included studies than included publications for cognitive emotion regulation.

2.2. CER: coordinate based meta-analysis and conjunction analysis with CRC

2.2.1. Literature search

PubMed and Web of Science were searched until 18/04/2018 using the keywords *emotion regulation AND (fMRI OR neuroimaging)*. Additional relevant studies were identified using reviews and reference lists (Fig. 1B). CER is typically studied by contrasting '*pure*' emotional stimulation (e.g., viewing aversive pictures) with emotional stimulation *during* CER (i.e., while re-appraising the stimulus). For example, when seeing the picture of a snake, re-appraising the situation as being part of an experiment typically decreases induced fear (Eippert et al., 2007). Thus, the experiment design in the selected CER studies contrasted two conditions: "*Emotional baseline*", in which subjects watched aversive pictures and were asked to naturally experience the emotional state elicited by the picture, and "*CER*", in which participants attempted to down-regulate their negative emotional responses towards the aversive pictures using reappraisal (Goldin et al., 2008; Gross, 2002; Ochsner et al., 2002).

Inclusion and exclusion criteria for studies were the same as for CRC (only visual stimuli, only down-regulation). Note that only studies using aversive stimuli were included. Furthermore, we selected only studies that employed reappraisal to modulate emotional responses; studies that used suppression or manipulation of attention such as distraction were excluded. These strict criteria were selected to achieve design homogeneity across CER and CRC studies, resulting in a smaller number of included studies than in other meta-analyses of CER (Morawetz et al., 2017b). Publications using identical subject samples were counted as one single study; thus, there were less included studies than included publications.

2.2.2. Meta-analysis and conjunction

Data extraction, meta-analysis, and post-hoc control analyses (see below for details) were conducted as for CRC, using MKDA (Wager et al., 2007). In addition, to control for the different number of included studies between CER (47 studies) and CRC (22 studies), we applied the following random-sampling procedure to CER: 22 CER studies were randomly selected over 100 iterations, additionally correcting for different sample sizes of the included studies (Supplementary Methods) (Crossley et al., 2014). Then we computed the average across these 100 density maps and used the result for further calculations. Due to our hypothesis, we only investigated the meta-analytic contrast "CER > Emotional baseline".

In order to find overlapping brain regions activated during both CER and CRC, we performed a conjunction analysis of the two individual meta-analyses, i.e., "CRC > Reward baseline" and "CER > Emotional baseline". To do that, we computed the union of p-value result maps of both individual analyses, correcting for potential errors in the estimation of p-values during individual meta-analyses ($p < 0.005$; see Supplementary Methods for details) (Radua et al., 2013).

In order to find differential activation patterns between CRC and CER, we investigated the meta-analytic contrast "(CER > Emotional baseline) > (CRC > Reward baseline)" and vice versa. Results were conjuncted with results of individual meta-analyses to ensure that activation differences were located in areas of significant activation.

2.3. Post-hoc control analyses

Several control analyses were conducted for both the CRC and the CER meta-analysis.

Jackknife analyses were performed to test for disproportionate effects of any single study on the results. The density statistic of each significant meta-analytic result cluster was iteratively recalculated (each time leaving out one study) and then compared to the original density statistic via χ^2-test (Etkin and Wager, 2007).

Furthermore, we conducted post-hoc analyses to test for disproportionate influences of the following variables on the results: (i) gender (only female, only male, or mixed), (ii) age (child [0–18 years], young adult [18–30 years], or older adult [more than 30 years]), (iii) cognitive control strategy sub-types (antecedent-focused, i.e., instruction was given before stimulus, or postcedent-focused, i.e., instruction was given during or after stimulus), (iv) stimulus type (e.g., food vs. non-food pictures), and (v) size of smoothing kernel. For each variable, studies were divided into categories as described above. Subsequently, the density statistic of each significant cluster was recalculated for each category and then compared to the other categories of this variable via χ^2-test (Kaiser et al., 2015).

2.4. Response inhibition: coordinate-based meta-analysis and conjunction of Go/NoGo and stop signal paradigms

PubMed and Web of Science were searched until 01/01/2019 using the keywords *("go nogo" OR "stop signal" OR "response inhibition") AND fMRI*. Additional relevant studies were identified using reviews and reference lists (Figure S1). We included all studies investigating a Go/NoGo or Stop signal task in healthy subjects following Langner and colleagues (Langner et al., 2018). Included studies are shown in Table S1. The experiment design in the selected studies contrasted two conditions: "Go", in which subjects performed a certain action, and "Stop" or "NoGo", in which subjects had to cognitively suppress this action. In this way, these experiments studied cognitive action control (Langner et al., 2018). Data extraction and meta-analysis were conducted as for CRC, using MKDA (Wager et al., 2007). In order not to confound our results by mixing two distinct experiment types, we conducted two separate meta-analyses: one for the contrast "Stop > Go" and one for the contrast "NoGo > Go". Then we performed a conjunction analysis across the results in the same way as for the CRC/CER conjunction ($p < 0.005$; see Supplementary Methods for details) (Radua et al., 2013).

2.5. Intrinsic functional connectivity analysis

To test whether the common CRC/CER activation pattern defines a permanently present network, we performed a seed-based whole-brain iFC-analysis of the meta-analytic conjunction result in an independent rs-fMRI dataset.

We used data from 80 healthy subjects (aged 25–27 years) that had undergone rs-fMRI scanning for 10min 52s (250 volumes, voxel size $= 3.59 \times 3.59 \times 3.59\,mm^3$) and T1-weighted MPRAGE scanning (voxel size $= 1 \times 1 \times 1\,mm^3$). Data were preprocessed with SPM12, including discarding of the first 5 scans for magnetization effects, motion correction, coregistration with T1, segmentation, normalization into Montreal Neurological Institute (MNI) space, and smoothing with a Gaussian kernel of 6 mm full-width at half-maximum (FWHM). No subject showed excessive head motion (cumulative motion translation or rotation >3 mm or 3° and mean point-to-point translation or rotation >0.15 mm or 0.1°). Finally, time series were despiked using ANFI's 3dDespike motion censoring procedure (http://afni.nimh.nih.gov/afni).

Seed time-courses were generated by extracting the time-courses of all voxels in the combined meta-analytic conjunction clusters and then performing principal component analysis to obtain one representative seed time-course, i.e., the first Eigen time series. iFC between the seed and each voxel in the brain was calculated via partial correlation, using the first Eigen time series of white matter signal, cerebrospinal fluid signal, and 6 head motion parameters as nuisance covariates (O'Reilly et al., 2010; Toulmin et al., 2015). Z-maps were constructed using Fisher's r-to-z transformation and significant voxels were detected by one-sample *t*-test in SPM ($p < 0.05$ family-wise error corrected, 50 voxels).

3. Results

In total, the literature search yielded a sample of 22 CRC studies with 741 subjects (Table 1, Fig. 1A), 47 CER studies with 1455 subjects

Table 1
Studies included in the CRC meta-analysis.

Author, year	Subjects (n)	Gender	Mean age	Stimulus type	CRC strategy	Contrast	FWHM of smoothing kernel (mm)
Brody et al. (2007)	42	12 F, 30 M	38	Cigarette videos	Resist any feelings	CRC > reward baseline, reward baseline > CRC	–
Crockett et al. (2013)	28	28 M	18–35	Erotic pictures	Think about large reward	CRC > reward baseline	8
Diekhof et al. (2012)	32	16 F, 16 M	F: 24.3 M: 24.7	Desire reason task	Think about long-term goal	reward baseline > CRC	9
Dietrich et al. (2016)	43	43 F	26.7	Food pictures	Individual mental strategy	CRC > reward baseline, reward baseline > CRC	8
Dong et al. (2016)	27	27 F	21.56	Chocolate delayed discounting task	Think about long-term goal	CRC > reward baseline	6
Giuliani et al. (2014)	50	33 F, 17 M	21.77	Food pictures	Reappraisal	CRC > reward baseline	6
Giuliani and Pfeifer, (2015)	60	60 F	16.66	Food pictures	Reappraisal	CRC > reward baseline	8
Harding et al. (2018)	30	14 F, 16 M	24.17	Food pictures	Individual preference	CRC > reward baseline, reward baseline > CRC	5
Hare et al. (2011)	33	23 F, 10 M	24.8	Food pictures	Think about healthiness	CRC > reward baseline	8
Hartwell et al. (2011)	32	19 F, 14 M	33.5	Pictures of people smoking	Resist the urge to crave	CRC > reward baseline, reward baseline > CRC	8
He et al. (2014)	30	17 F, 13 M	19.7	Food pictures	Inhibit responses to appetizing food items	CRC > reward baseline	5
Hill et al. (2017)	26	19 F, 7 M	24	Monetary reward	Think about long-term goal	CRC > reward baseline	8
Hollmann et al. (2012)	17	17 F	25.3	Food pictures	Reinterpret	CRC > reward baseline	8
Hutcherson et al. (2012)	26	9 F, 17 M	22	Food pictures	Decrease craving	CRC > reward baseline, reward baseline > CRC	8
Kober et al. (2010)	21	9 F, 12 M	26.8	Food and cigarette pictures	Think about long-term consequences	CRC > reward baseline, reward baseline > CRC	6
McClure et al. (2004)	14	9 F, 5 M	21.4	Monetary reward	Think about long-term goal	reward baseline > CRC	8
Norman et al. (2017)	20	20 M	12–18	Monetary reward: delay discounting task	Think about long-term goal	CRC > reward baseline, reward baseline > CRC	–
Petit et al. (2016)	23	10 F,13 M	25.91	Food pictures	Think about benefits of eating healthy food	CRC > reward baseline	8
Silvers et al. (2014)	105	71 F, 34 M	14.27	Food pictures	Imagine food far away	CRC > reward baseline, reward baseline > CRC	6
Tuulari et al. (2015)	41	41 F	44.9	Food pictures	Inhibit of eating urge	CRC > reward baseline, reward baseline > CRC	8
van der Laan et al. (2014)	20	20 F	21.2	Food pictures	Watch weight	CRC > reward baseline, reward baseline > CRC	8
Yokum and Stice (2013)	21	13 F, 8 M	15.2	Food pictures	Think about consequences and benefits	CRC > reward baseline, reward baseline > CRC	6

Table 1. Only studies in which subjects had to resist craving towards a reinforcing stimulus in the "CRC" condition were included in the meta-analysis. During "reward baseline", subjects 'naturally' experienced the craving elicited by the stimulus. Stimulus type describes what type of material was employed: food/cigarettes pictures, videos, or others. CRC strategy indicates which strategy participants used to reduce craving: descriptive terms were copied from the papers.

(Table 2, Fig. 1B), and 50 response inhibition studies with 1042 subjects (Table S1; Figure S1).

3.1. Activation pattern of CRC: meta-analysis of cognitive reward control, CRC > Reward baseline

Significant stronger activation during CRC compared to reward baseline was found for bilateral SMA, pre-SMA, dlPFC, vlPFC, anterior insulae, and angular gyrus (Table 3, Fig. 2).

3.2. Activation pattern of CER: meta-analysis of cognitive emotion regulation, CER > Emotional baseline

We found significant stronger activation during CER compared to baseline emotion mainly in bilateral dlPFC, vlPFC, SMA, and pre-SMA (Table 4, Fig. 3). Additional clusters were located in temporal gyrus (superior, middle, and inferior), angular gyrus, anterior and posterior cingulate cortex, precentral gyrus, caudate nucleus, occipital cortex, and cerebellum.

3.3. Post-hoc control analyses for both CRC and CER

Jackknife analyses showed that no single study had a significant effect on the results of the individual, i.e., "CRC > Reward baseline" and "CER > Emotional baseline", or difference, i.e., " (CER > Emotional baseline) > (CRC > Reward baseline)", meta-analyses ($p \geq 0.78$ for each significant result cluster across all contrasts). Therefore, the reported results include all studies. Further post-hoc analyses revealed no disproportionate influence of the variables gender ($p \geq 0.51$), age ($p \geq 0.31$), cognitive control strategy ($p \geq 0.44$), stimulus type ($p \geq 0.36$), and smoothing kernel ($p \geq 0.47$). Additional control analyses are reported in Supplementary Results.

3.4. CRC and CER activation patterns

3.4.1. Common activation patterns of CRC and CER

To test for brain regions that are activated during both CRC and CER, we conducted a conjunction analysis of the contrasts "CRC > Reward baseline" and "CER > Emotional baseline". We found significant overlap in the following regions: bilateral SMA, pre-SMA, dlPFC, vlPFC, and

Table 2
Studies included in the CER meta-analysis.

Author, year	Subjects (n)	Gender	Mean age	Stimulus type	CER strategy	Contrast
Belden et al. (2014)	19	8 F, 11M	10.05	Pictures: IAPS	Reint	CER > emotional baseline
Denny et al. (2015)	17	12 F, 5 M	24.1	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Domes et al. (2010)	33	17 F, 16 M	F: 24.6 M: 25.2	Pictures: IAPS	Both	CER > emotional baseline
Dorfel et al. (2014)	36	36 F	18–39	Pictures: IAPS	Both	CER > emotional baseline, emotional baseline > CER
Doré et al. (2017)	20	12 F, 8 M	24.6	Pictures: IAPS	Reint	CER > emotional baseline
Eippert et al. (2007)	24	24 F	23.30	Pictures: IAPS	Both	CER > emotional baseline
Engen and Singer (2015)	15	5 F, 10 M	56.1	Film clip	Reint	CER > emotional baseline, emotional baseline > CER
Erk et al. (2010)	17	8 F, 9 M	43.9	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Goldin et al. (2008)	17	17 F	22.7	Videos	Reint	CER > emotional baseline
Hallam et al. (2015)	40	20 F, 20 M	20	Pictures: IAPS	Distance	CER > emotional baseline
Hayes et al. (2010)	25	11 F, 14 M	21.6	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Koenigsberg et al. (2009) + (2010)	16	9 F, 7 M	31.8	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Krendl et al. (2012)	16	10 F, 6 M	21.6	Pictures: IAPS	Both	CER > emotional baseline, emotional baseline > CER
Lang et al. (2012)	15	15 F	24.73	Scripts: ANET	Distance	CER > emotional baseline
Leiberg et al. (2012)	24	24 F	24.1	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Mak et al. (2009a)	12	12 F	24	Pictures: IAPS	Subjects' choice	CER > emotional baseline, emotional baseline > CER
Mak et al. (2009b)	24	12 F, 12 M	F: 24 M: 24	Pictures: IAPS	Subjects' choice	CER > emotional baseline
McRae et al. (2008)	25	13 F, 12 M	20.6	Pictures: IAPS	Reint	CER > emotional baseline
McRae et al. (2010)	18	18 F	24.4	Pictures: IAPS	Reint	CER > emotional baseline
McRae et al. (2012)	38	21 F, 17M	F: 16.75 M: 16.10	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Modinos et al. (2010)	18	7 F, 11M	21.1	Pictures: IAPS	Reint	CER > emotional baseline
Morawetz et al. (2016a)	59	20 F, 39 M	32.47	Film clip (extrem sports)	Both	CER > emotional baseline
Morawetz et al. (2016b)	60	30 F, 30 M	30.48	Pictures: FACES	Both	CER > emotional baseline, emotional baseline > CER
Morawetz et al. (2017a)	23	12 F, 11 M	25.70	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Mulej Bratec et al. (2015)	20	20 F	24.8	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Nelson et al. (2015)	22	11 F, 11 M	25.2	Pictures	Reint	CER > emotional baseline
New et al. (2009)	14	14 F	31.7	Pictures: IAPS	Reint	CER > emotional baseline
Ochsner et al. (2002)	15	15 F	21.9	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Ochsner et al. (2004)	24	24 F	20.6	Pictures: IAPS	Both	CER > emotional baseline, emotional baseline > CER
Paschke et al. (2016)	108	55 F	26.12	Pictures: EPS	Distance	CER > emotional baseline
Perlman et al. (2012)	14	6 F, 8 M	15.1	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Phan et al. (2005)	14	8 F, 6 M	27.6	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Pitskel et al. (2011)	15	6 F, 9 M	13.03	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Qu and Telzer (2017)	29	14 F, 15 M	19.2	Photos	Reint	CER > emotional baseline, emotional baseline > CER
Sarkheil et al. (2015)	14	8 F, 6 M	20–27	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Schulze et al. (2011)	15	15 F	24.53	Pictures: IAPS	Both	CER > emotional baseline, emotional baseline > CER
Silvers et al. (2015a)	56	31 F, 25 M	16.45	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Silvers et al. (2015b)	30	13 F, 17 M	21.97	Pictures: IAPS	Reint	CER > emotional baseline
Silvers et al. (2017)	112	65 F, 47 M	15.73	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Sripada et al. (2014)	49	23 F, 26 M	23.63	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Stephanou et al. (2016) + (2017)	78	44 F, 34 M	19.91	Pictures: IAPS, EPS, online	Reint	CER > emotional baseline, emotional baseline > CER

(*continued on next page*)

Table 2 (*continued*)

Author, year	Subjects (n)	Gender	Mean age	Stimulus type	CER strategy	Contrast
Uchida et al. (2015)	62	32 F, 30 M	22.3	Pictures: IAPS	Reint	CER > emotional baseline, emotional baseline > CER
Vanderhasselt et al. (2013)	42	42 F	21.26	Pictures: IAPS	Reint	CER > emotional baseline
Walter et al. (2009)	18	18 F	24	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Winecoff et al. (2011)	42	n.a.	25	Pictures: IAPS	Distance	CER > emotional baseline, emotional baseline > CER
Winecoff et al. (2013)	31	21 F, 10 M	F: 23.1 M: 69	Pictures: IAPS	Distance	CER > emotional baseline
Zaehringer et al. (2018)	20	13 F, 7 M	39.65	Pictures: IAPS	Distance	CER > emotional baseline

Table 2. Only studies in which subjects had to down-regulate their emotional responses to aversive visual stimuli using reappraisal strategies in the "CER" condition were included in the meta-analysis. During "emotional baseline", subjects 'naturally' experienced the emotional state elicited by the stimulus. Stimulus type describes what type of material was employed: pictures (IAPS: International Affective Picture System; EPS: Emotional Picture Set), videos or scripts (ANET: Affective Norms for English Text). CER strategy indicates whether participants had to reinterpret (reint), distance themselves (distance), or use a combination of both strategies (both).

Table 3
Results of meta-analysis CRC > Reward baseline.

Anatomical region	Hemisphere	MNI peak coordinates of effect(s)			Cluster size (voxels)	Maximum density value	p-value, FWER-corrected	
		x	y	z				
Frontal Operculum	L	−46	28	0	391	0.422	<0.0001	hb
Middle Frontal Gyrus	L	−44	8	42	506	0.456	0.0007	hb
Angular Gyrus	R	52	−52	38	15	0.311	0.0172	hb
Angular Gyrus	R	46	−54	44	10	0.320	0.0101	hb
Supplementary Motor Area and pre-Supplementary Motor Area	R/L	0	18	54	614	0.489	<0.0001	hb
Inferior Frontal Gyrus	L	−44	24	14	3494	0.289	<0.0001	eb
Frontal Orbital Cortex	R	44	24	−6	439	0.266	0.0090	eb
Superior Temporal Gyrus, posterior division	L	−54	−34	2	362	0.218	0.0253	eb
Angular Gyrus	L	−52	−54	32	1214	0.283	<0.0001	eb
Supplementary Motor Area and pre-Supplementary Motor Area	L	−2	20	54	1756	0.288	<0.0001	eb
Angular Gyrus	R	52	−54	40	531	0.285	0.0030	eb
Inferior Frontal Gyrus, pars triangularis	L	−44	32	12	2345	0.206	<0.0001	eb
Insular Cortex	R	40	22	12	1657	0.289	0.0011	eb
Angular Gyrus	L	−36	14	−16	15	0.156	<0.0001	eb
Angular Gyrus	L	−50	−58	20	57	0.136	0.0003	eb
Angular Gyrus	L	−48	−54	40	905	0.183	0.0003	eb
pre-Supplementary Motor Area	L	−8	36	42	1592	0.183	<0.0001	eb
Middle Frontal Gyrus	R	30	32	26	4035	0.166	<0.0001	eb
Frontal Operculum	L	−38	24	10	1485	0.150	0.0008	eb
Frontal Pole	L	−48	52	−6	86	0.122	0.0008	eb
Frontal Pole	L	−28	44	30	90	0.097	<0.0001	eb
Middle Frontal Gyrus	R	46	28	40	59	0.133	<0.0001	eb
Supplementary Motor Area and pre-Supplementary Motor Area	R	6	24	38	103	0.134	<0.0001	eb
Supplementary Motor Area and pre-Supplementary Motor Area	L	−4	10	40	39	0.134	<0.0001	eb
Supplementary Motor Area	R	10	10	46	15	0.130	<0.0001	eb
Middle Frontal Gyrus	L	−30	4	56	19	0.123	0.0008	eb
Middle Frontal Gyrus	L	−40	10	60	55	0.134	0.0008	eb

Table 3. Clusters of stronger activation for cognitive reward control (CRC), significant at $p < 0.05$ (FWER-corrected) based on MKDA meta-analysis. Both results for height-based (hb) and extent-based (eb) threshold are reported. Labels of anatomical regions were derived from Harvard-Oxford brain atlas and Automated Anatomical Labelling (AAL) atlas. Hemispheres are indicated (L = left, R = right). Peak coordinates represent coordinates with maximum density value (i.e., maximum weighted proportion of studies reporting a peak within 15 mm of this voxel). MNI = Montreal Neurological Institute.

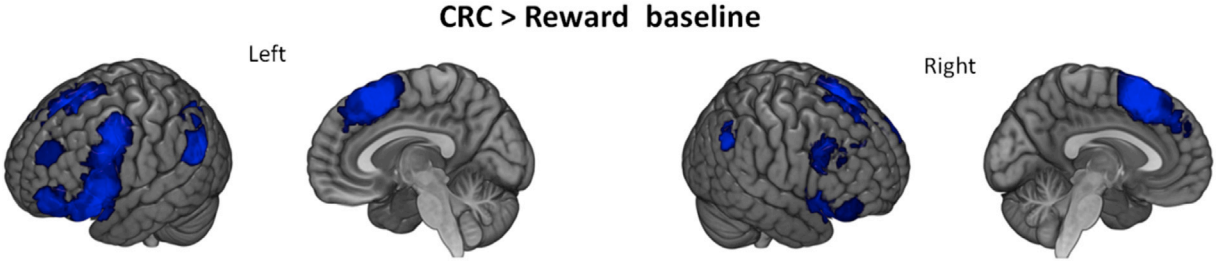

Fig. 2. Activation during cognitive reward control.
Brain regions showing consistent activation during cognitive reward control (CRC). Results were calculated by Multilevel Kernel Density Analysis (MKDA) meta-analysis and are significant for $p < 0.05$ (both height-based and extent-based threshold).

Table 4
Results of meta-analysis CER > Emotional baseline.

Anatomical region	Hemisphere	MNI peak coordinates of effect(s)			Cluster size (voxels)	Maximum density value	p-value, FWER-corrected	
		x	y	z				
Inferior Frontal Gyrus, pars triangularis	L	−50	28	−4	1634	0.461	<0.0001	hb
Middle Temporal Gyrus, posterior division	L	−58	−38	−4	1149	0.418	<0.0001	hb
Frontal Orbital Cortex	R	48	26	−4	529	0.323	0.0003	hb
Lateral Occipital Cortex, superior division	L	−48	−62	34	1230	0.454	<0.0001	hb
Angular Gyrus	R	54	−58	32	277	0.353	<0.0001	hb
Middle Frontal Gyrus	R	40	22	42	695	0.339	0.0003	hb
Supplementary Motor Area and pre-Supplementary Motor Area	L	−4	20	54	2228	0.528	<0.0001	hb
Middle Frontal Gyrus	L	−40	10	48	1105	0.411	<0.0001	hb
Cerebellum	R	36	−64	−32	391	0.175	0.0003	eb
Cingulate Gyrus, anterior division	R	2	24	30	8766	0.241	<0.0001	eb
Angular Gyrus	L	−52	−50	18	2304	0.241	<0.0001	eb
Middle Temporal Gyrus, posterior division	R	58	−32	−4	233	0.194	0.0253	eb
Angular Gyrus	R	56	−58	26	967	0.240	<0.0001	eb
Cingulate Gyrus, posterior division	L	−2	−24	28	293	0.162	0.0030	eb
Paracingulate Gyrus	L	−2	32	26	7689	0.193	<0.0001	eb
Supramarginal Gyrus, posterior division	L	−50	−48	16	1421	0.158	<0.0001	eb
Angular Gyrus	R	46	−54	32	624	0.166	0.0037	eb
Middle Frontal Gyrus	R	42	6	50	92	0.152	<0.0001	eb
Caudate nucleus extending to insula and frontal operculum	L	−12	22	10	9723	0.177	<0.0001	eb
Angular Gyrus	L	−46	−56	14	1011	0.114	<0.0001	eb
Superior Temporal Gyrus	L	−46	−30	0	12	0.110	<0.0001	eb
Planum Temporale	L	−52	−36	10	15	0.111	<0.0001	eb
Precentral Gyrus	L	−60	8	18	33	0.113	<0.0001	eb
Lateral Occipital Cortex, superior division	L	−40	−68	18	23	0.111	<0.0001	eb
Precentral Gyrus	L	−52	0	42	59	0.113	<0.0001	eb
Precentral Gyrus	L	−46	−6	50	15	0.111	<0.0001	eb
Middle Frontal Gyrus	L	−30	4	64	140	0.114	<0.0001	eb
Supplementary Motor Area	L	−10	2	52	12	0.114	<0.0001	eb

Table 4. Clusters of stronger activation for cognitive emotion regulation (CER), significant at $p < 0.05$ (FWER-corrected) based on MKDA meta-analysis. Both results for height-based (hb) and extent-based (eb) threshold are reported. Labels of anatomical regions were derived from Harvard-Oxford brain atlas and Automated Anatomical Labelling (AAL) atlas. Hemispheres are indicated (L = left, R = right). Peak coordinates represent coordinates with maximum density value (i.e., maximum weighted proportion of studies reporting a peak within 15 mm of this voxel). MNI = Montreal Neurological Institute.

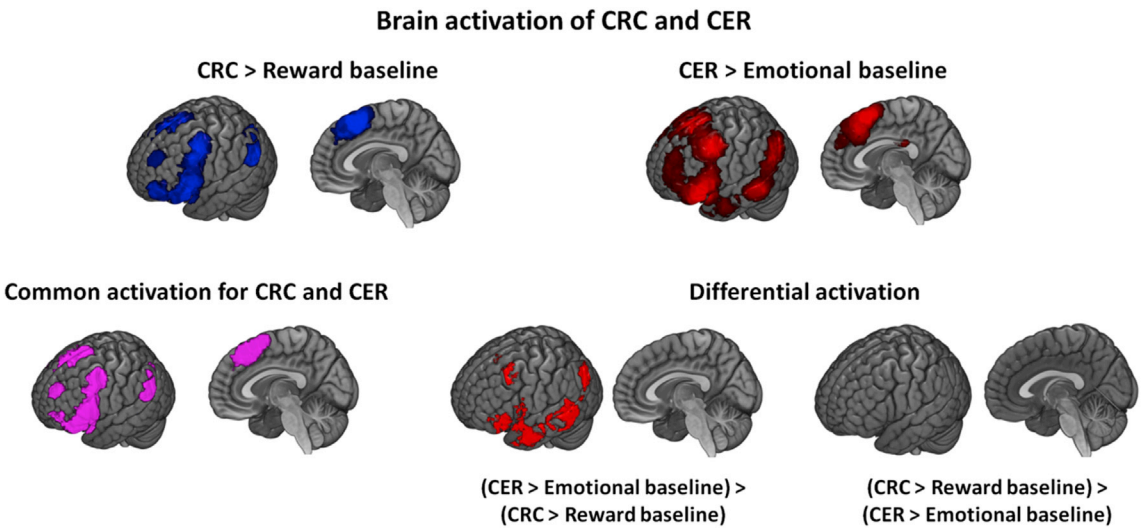

Fig. 3. Cognitive reward control and cognitive emotion regulation.
Top row: Brain regions showing consistent activation during cognitive reward control (CRC) and cognitive emotion regulation (CER). Results were calculated by Multilevel Kernel Density Analysis (MKDA) meta-analysis and are significant for $p < 0.05$ (both height-based and extent-based threshold). Bottom row: Left: Brain regions of common activation during both CRC and CER, calculated by conjunction of both single meta-analytic result-maps ($p < 0.005$). Right: Brain regions showing differential activation between CER and CRC. Results were calculated by Multilevel Kernel Density Analysis (MKDA) meta-analysis and are significant for $p < 0.05$ (both height-based and extent-based threshold).

anterior insulae, as well as left angular and superior temporal gyrus (Table 5, Fig. 3).

3.4.2. *Differential activation patterns of CRC and CER*

To complement the conjunction analysis, we also tested for regions with increased stronger activation during CER compared to CRC and vice versa.

3.4.2.1. (CER > emotional baseline) > (CRC > reward baseline). We identified clusters with significantly increased stronger activation during

Table 5
Common activation pattern across CRC and CER.

Anatomical region	Hemisphere	MNI peak coordinates of effect(s)			Cluster size (voxels)	Conjunction p-value
		x	y	z		
(CRC > Reward baseline) ∩ (CER > Emotional baseline)						
Supplementary motor area, pre-Supplementary motor area, dorsolateral and ventrolateral prefrontal cortex	R	6	26	50	9157	0.002
Anterior insula, ventrolateral and dorsolateral prefrontal cortex	L	−34	32	−4	6532	0.00173
Angular gyrus	L	−54	−66	26	1700	0.0000168
Angular gyrus	R	54	−54	38	392	0.000517
Superior temporal gyrus	L	−50	−32	0	361	0.00112

Table 5. Clusters of common activation across cognitive reward control (CRC) and cognitive emotion regulation (CER), based on conjunction ($p > 0.005$). Hemispheres are indicated (L = left, R = right). MNI = Montreal Neurological Institute.

Table 6
Activation differences between CER and CRC.

Anatomical region	Hemisphere	MNI peak coordinates of effect(s)			Cluster size	p-value
		x	y	z		
A. (CER > Emotional baseline) > (CRC > Reward baseline)						
Superior and medial temporal gyrus, angular gyrus, ventrolateral prefrontal cortex	L	−48	14	−12	6792	0.00226
pre-Supplementary motor area	L	−16	26	56	546	0.000971
Angular gyrus	R	48	−62	34	446	0.00000289
B. (CRC > Reward baseline) > (CER > Emotional baseline)						
–	–	–	–	–	–	–

Table 6. (A) Clusters of differentially stronger activation during CER than during CRC, significant at $p < 0.05$ (FWER-corrected) based on MKDA meta-analysis. Hemispheres are indicated (L = left, R = right). MNI = Montreal Neurological Institute.
(B) No clusters of differentially greater activation during CRC than during CER were observed at $p < 0.05$ (FWER-corrected).

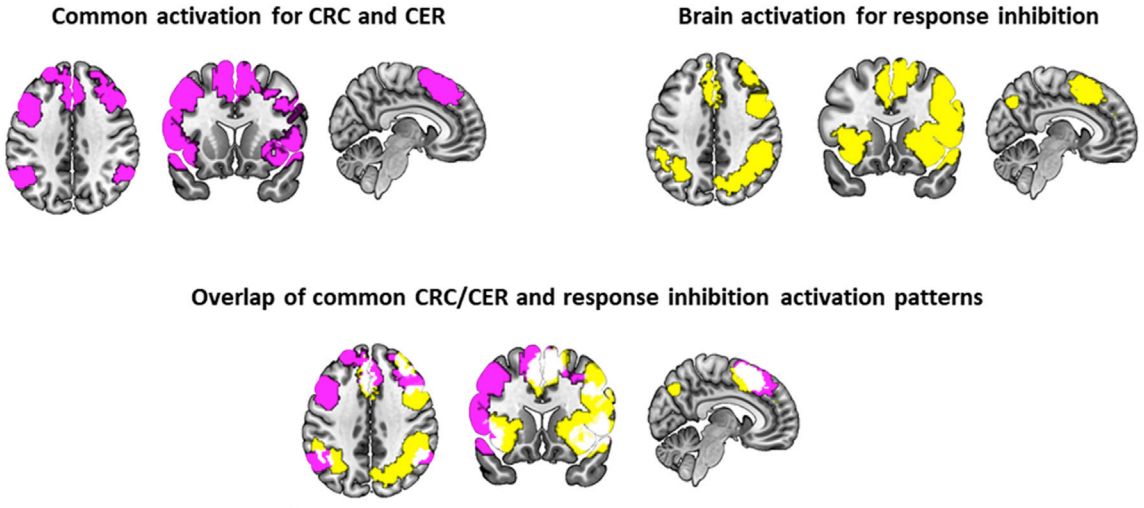

Fig. 4. Activation patterns of CRC/CER and response inhibition.
Top row: Left: Common brain activation pattern of cognitive reward control (CRC) and cognitive emotion regulation (CER), shown in violet (see Fig. 3). Right: Brain regions showing consistent activation during response inhibition (yellow). Results were calculated by Multilevel Kernel Density Analysis (MKDA) meta-analysis and subsequent conjunction ($p < 0.005$). Bottom row: Visual overlap of CRC (violet) and response inhibition (yellow) activation patterns. Overlap is depicted in white.

CER than during CRC in bilateral angular gyrus, left superior and medial temporal gyrus, and parts of left vlPFC and pre-SMA (Table 6, Fig. 3).

3.4.2.2. (CRC > reward baseline) > (CER > emotional baseline). No brain regions showed significantly increased stronger activation during CRC than during CER (Table 6, Fig. 3).

3.5. Common and distinct activation patterns of CRC/CER and response inhibition

We identified several clusters of consistent activation during response inhibition, covering right vlPFC and dlPFC, bilateral angular/supramarginal gyrus (but focused on the right hemisphere), SMA and pre-SMA, anterior insula and putamen (Fig. 4). The response inhibition activation

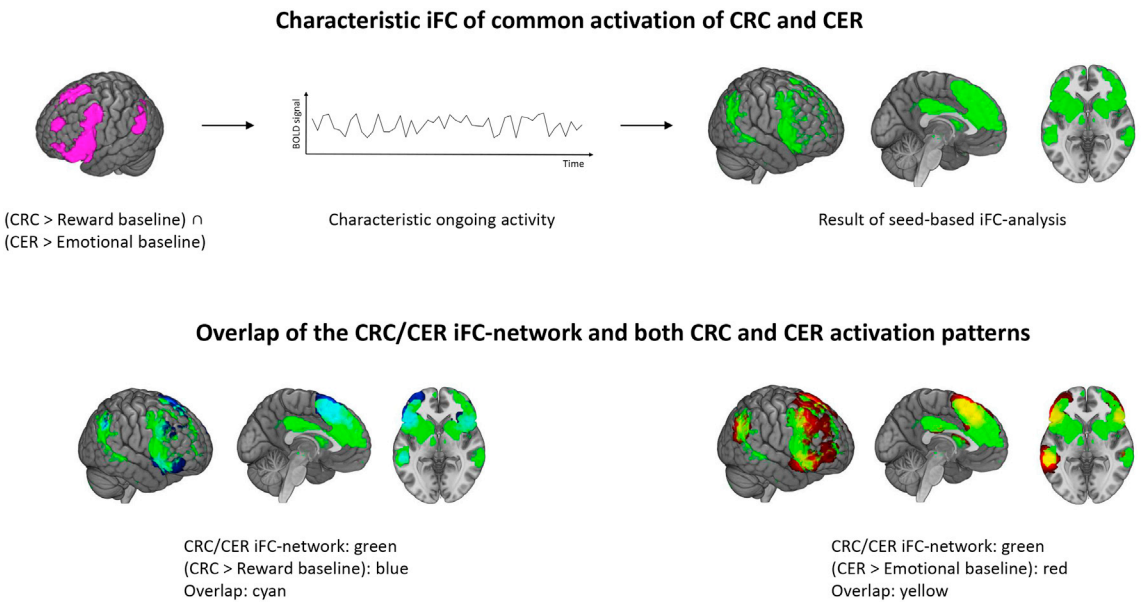

Fig. 5. Intrinsic functional connectivity network of the CRC/CER common activation pattern.
Top row: the averaged blood oxygenation time course of the common CRC/CER activation cluster (violet, see Fig. 3) was extracted for each subject's rs-fMRI data of an independent sample of 80 healthy controls, and iFC with each voxel in the brain was calculated via partial correlation. The resulting across-subjects pattern of significant iFC with the common activation cluster ($p < 0.05$ family-wise error corrected, 50 voxels) is depicted in green. Bottom row: Visual overlap of the common CRC/CER iFC-network and meta-analytic result clusters for CRC and CER based on Multilevel Kernel Density Analysis ($p < 0.05$, see Figs. 2 and 3).

pattern overlapped with the common CRC/CER activation pattern in SMA/pre-SMA, anterior insula, and angular/supramarginal gyrus (Fig. 4). However, the activation pattern for response inhibition focused on the right hemisphere, while the common CRC/CER activation pattern was distributed rather symmetrically with a slightly stronger representation in the left hemisphere. There was more extensive activation of right vlPFC, dlPFC, and angular/supramarginal gyrus for response inhibition, while the left vlPFC and dlPFC were consistently activated only during CRC and CER.

3.6. iFC-network of the common CRC/CER activation pattern

IFC was defined as seed-based iFC, with the combined common CRC/CER activation clusters as seed. Clusters of significant iFC ($p < 0.05$ family-wise error corrected, 50 voxels) were located in bilateral striatum, anterior thalamus, anterior insula, anterior and posterior cingulum, dorsomedial PFC (dmPFC), pre-SMA, SMA, dlPFC, vlPFC, angular/supramarginal gyrus, and superior and medial temporal gyrus (Fig. 5). This iFC-network covered both the CRC and the CER activation pattern (although some parts of the CER activation pattern in vlPFC/dlPFC were more extensive than the iFC-network) (Fig. 5).

4. Discussion

This study investigated the following questions: first and mainly, is there a consistent pattern of brain activation in CRC across stimulus types? Second, does a common activation pattern exist for CRC (i.e., control of motivational states) and CER (i.e., control of aversive emotional states)? Third, how does common CRC/CER activation link with activation during control of action states with less motivational/emotional valence, such as response inhibition? Fourth, does the common CRC/CER activation pattern constitute a permanently present intrinsic co-activity network? We collected fMRI activation studies in CRC, CER, and response inhibition and conducted a coordinate-based meta-analysis followed by conjunction; these analyses were complemented by a seed-based iFC-analysis in an independent rs-fMRI dataset. First, we identified consistent CRC activation across stimulus types mainly in supplementary motor area, pre-supplementary motor area, ventrolateral and dorsolateral prefrontal cortices. Second, we found that this activation pattern overlapped largely with CER-related activation. This link between CRC and CER supports models of a common neurocognitive mechanism for CRC and CER, generating cognitive control of both reward and negative emotions. Third, this common CRC/CER activation pattern overlapped with the response inhibition activation pattern in (pre-)supplementary motor, insular, and parietal cortices, but differed from it in dorsolateral and ventrolateral prefrontal cortices. This distinct pattern of response inhibition in comparison to CRC/CER suggests common and distinct processes for the control of stimuli with more or less affective valence. Fourth, the common CRC/CER activation pattern defined an iFC-network at rest covering CRC/CER activation patterns during task conditions, both indicating the intrinsic network character of the CRC/CER pattern and supporting a common underlying mechanism of motivational and emotional control. We suggest that model-based decision-making might be a candidate for such a common mechanism, which we will discuss in detail below.

4.1. Consistent activation in CRC across stimulus types

The CRC meta-analysis revealed that brain regions in bilateral SMA, pre-SMA, vlPFC, dlPFC, anterior insula, and angular gyrus were consistently more strongly activated during CRC than during reward cue exposure without control (Fig. 2). To the best of our knowledge, this was the first coordinate-based meta-analysis of fMRI-studies in the field of CRC that investigated studies across stimulus types. We restricted the included literature to studies using paradigms in which subjects viewed pictures/videos of rewarding stimuli and had to control their craving towards these stimuli in the "CRC" condition (Brody et al., 2007; Kelley et al., 2015; Kober et al., 2010). Distinct paradigms, e.g., involving depletion of self-regulatory resources (Wagner et al., 2013), were not considered in order to avoid methodological inconsistencies. We ensured maximal coverage of the existing literature by including studies with a wide range of rewarding stimuli, for example money, food, sex, or cigarette smoking (Table 1). To ensure that no particular stimulus type (e.g., food pictures) had a disproportionate influence on the results, we conducted post-hoc analyses to control for this factor. These analyses showed no significant effect of a specific stimulus type. Further control

analyses demonstrated that no single study significantly influenced results; for the factors age, gender, cognitive control strategy (i.e., antecedent- or postcedent-focused), or smoothing kernel size, such an influence was unlikely.

Our results support recent theoretical suggestions and a qualitative review by Kelley and colleagues, hypothesizing that lateral PFC, ventromedial PFC, and anterior cingulate cortex are critical for CRC (their concept of "self-regulation" is very akin to our concept of CRC) (Kelley et al., 2015). While we could confirm consistent activation in lateral prefrontal cortices during CRC, we did not observe robust activation in ventromedial PFC and anterior cingulate. Lateral PFC is thought to be more involved in cognitive aspects of self-regulation (e.g., planning), while ventromedial PFC activation might rather reflect adverse consequences of excessive behavior (Kelley et al., 2015). As we restricted studies to be based on paradigms of *cognitive* reward control, our results seem well in line with these predictions.

Furthermore, our findings extend the recent meta-analysis of Han and colleagues, which reported consistent activation in SMA, pre-SMA, lateral PFC, insula, and parietal cortices during dietary self-control (Han et al., 2018). We also included other stimuli like cigarettes or erotic pictures and observed a similar pattern, although more extended in lateral PFC. This suggests that the activation pattern relevant for food-control is comprised within a slightly larger pattern for domain-general cognitive control of hedonic stimuli. So in summary, results indicate that SMA, pre-SMA, and lateral fronto-parietal cortices are consistently activated during CRC across a wide range of rewarding stimuli.

4.2. Common activation in CRC and CER; more distinct activation in response inhibition

Combining the results of the CRC meta-analysis with the CER meta-analysis, we showed that activation patterns of CRC and CER converged on bilateral SMA, pre-SMA, dlPFC, and vlPFC, as well as on insular, parietal, and temporal cortices (Fig. 3).

This result is composed of several subresults:

(i) Consistent activation during CER comprised bilateral vlPFC, dlPFC, SMA, pre-SMA, cingulate, temporal, parietal, and subcortical regions (Fig. 3). These results confirm almost exactly results of several previous meta-analyses of reappraisal studies, which also highlighted regions in dlPFC, vlPFC, SMA, pre-SMA, temporal, and parietal cortices (Buhle et al., 2014; Kohn et al., 2014; Langner et al., 2018; Morawetz et al., 2017b), thereby confirming the reliability of our meta-analytic approach. Moreover, the findings were not affected by any single study, age, gender, or regulation strategy, as shown by post-hoc control analyses.

(ii) We linked CRC and CER activation via conjunction analysis. This analysis revealed a common multi-regional activation pattern in bilateral SMA, pre-SMA, dlPFC, vlPFC as well as anterior insula, left angular and superior temporal gyrus (Fig. 3). We controlled for the divergent number of studies included for CRC and CER by random-sampling of CER studies, which is a validated strategy in meta-analyses (Crossley et al., 2014; Sha et al., 2017). While CRC controls approach behavior towards rewarding stimuli, CER controls avoidance behavior regarding aversive stimuli (Corr and McNaughton, 2012). This conceptualization suggests overlapping mechanisms and complementary activation patters. According to appraisal models of emotions (Gross and Barrett, 2011), negative emotions arise from the valuation of an aversive stimulus, which then leads to a certain outcome action, namely avoidance behavior. During cognitive regulation of negative emotions (CER), the emotion itself becomes the subject of valuation via cognitive reappraisal, and the emotional response is the outcome action that is altered by emotion regulation (Etkin et al., 2015; Gross and Barrett, 2011). Like aversive stimuli, also rewarding stimuli are valuated, leading not to avoidance behavior but to craving and approach behavior. During cognitive reward control, the craving becomes the subject of cognitive valuation and modulation. In this way, CRC is mechanistically very similar to CER, as they both involve cognitive reappraisal (either of a negative emotion or of craving towards a rewarding stimulus).

Deepening this line of thought in terms of cognitive mechanisms of re-appraisal, common activation across CER and CRC is consistent with a recent theory suggesting shared model-based control mechanisms for CER and reward-related decision-making such as CRC (Etkin et al., 2015). Etkin and colleagues suggested particularly that vlPFC, dlPFC, SMA, and pre-SMA are critically involved in CER due to their typical involvement in reward model-based decision-making. This overlap of suggested and observed common activation across CER and CRC with its implications for underlying model-based control mechanisms will be discussed in detail further below in paragraph 3 of the discussion.

(iii) When testing for differences in activation patterns between CRC and CER, CER was found to selectively recruit a larger activation pattern than CRC in bilateral angular gyrus, left superior and medial temporal gyrus, and parts of left vlPFC and pre-SMA (Fig. 3). In contrast, CRC did not show any differentially larger activation pattern than CER. A possible explanation for the selectively larger activation pattern of CER in predominantly left-sided cortical regions, which are essentially involved in language functions (Knecht et al., 2000), might be an association between language function and CER-reappraisal. CER-reappraisals comprise re-interpretation of a stimulus and its situation, which is often guided by language-based re-formulation (e.g., 'this stimulus is not real, but part of an experiment') and which therefore may recruit relatively more language-relevant regions than CRC (Ochsner et al., 2012).

Notably, a very recent meta-analysis addressed a related question: do neural patterns of CER overlap with cognitive action control (comprising a wide range of tasks like response inhibition, response conflicts, or task switching) (Langner et al., 2018)? Of note, Langner and colleagues did not include CRC studies in their analysis and thus investigated a different research question. They found activation overlaps between CER and cognitive action control in pre-SMA, vlPFC, insula, and temporo-parietal junction, but rather extended activation differences in prefrontal and parietal cortices. Our results showed a slightly different pattern: the pattern of overlapping activation for CRC and CER was more pronounced than for CER and cognitive action control, while the activation differences between CER and CRC were more restricted than between CER and cognitive action control (however, Langner and colleagues' results were also dominated by greater activation during CER). Taken together, the larger overlap between CRC and CER as opposed to between CER and cognitive action control suggests that activation patterns of control of motivational and emotional states are more similar to each other than to activation patterns of control of states with less affective valence (as in cognitive action control).

To further investigate whether our results of common control are specific to CRC and CER or rather reflect a general pattern of cognitive control of states/responses to stimuli with and without affective valence, we analyzed brain activations during the control of actions with less affective valence than those of motivational and emotional states of CRC and CER. Specifically, we performed a further meta-analysis of studies of response inhibition, in which actions in response to certain stimuli are suppressed or inhibited. We identified consistent activation during response inhibition in right vlPFC and dlPFC, in mostly right-hemispheral parietal cortices, and bilateral SMA, pre-SMA, anterior insula and putamen (Fig. 4). This activation pattern overlapped partly with the common CRC/CER activation pattern. However, and interestingly, the activation pattern for response inhibition focused on the right hemisphere, while

the common CRC/CER activation pattern had a slightly stronger representation in the left hemisphere, leading to distinct activation patterns mostly in dlPFC, vlPFC, and parietal cortices.

An interpretation of these distinct hemispherical focuses could be that environment-focused response inhibition recruits right-centered attention networks subserving reorienting functions (such as a right-lateralized ventral attention network (Corbetta et al., 2000; Corbetta et al., 2008; Fox et al., 2006)), while cognitive regulation of motivational and emotional states relies more heavily on bilateral frontoparietal cortices (Etkin et al., 2015; Kelley et al., 2015). This is in line with a previous finding that the control of states of high emotional valence is associated with increased interactions across networks focused on prefrontal cortices (Brandl et al., 2018).

Taken together, common CRC/CER activation partly overlapped with activation during control of actions with less motivational/emotional valence, but the activation difference indicates specificity for the control of states with affective valence.

4.3. CRC/CER intrinsic co-activity network

To address the question whether a common CRC/CER activation pattern constitutes a permanently present intrinsic co-activity network, we complemented the meta-analyses by a seed-based iFC-analysis using the common CRC/CER activation pattern as seed. The iFC-network defined in this way covered bilateral SMA, pre-SMA, dlPFC, vlPFC, striatum, thalamus, as well as insular, cingular, parietal and temporal cortices (Fig. 5). This network covered the CRC activation pattern completely and most of the CER activation pattern. Moreover, the iFC-network was only slightly larger than the CRC and CER activation patterns, focusing on fronto-parietal cortices. In other words, the CRC/CER activation pattern is also present during resting-state, in a remarkably similar appearance than during task states. These results suggest that the identified CRC/CER activation pattern is, in the form of an intrinsic co-activity network, permanently present in the intrinsic organization of brain activity.

This specific issue mirrors a more general theme, namely that organized ongoing brain activity both reflects previous and shapes future cognitive task activations in general (Berkes et al., 2011; Cole et al., 2016; Rosenberg et al., 2016; Smith et al., 2009; Tavor et al., 2016). In other words, the healthy subjects studied in this extension analysis seem to have employed CRC and CER strategies multiple times in their lives, which has left an imprint in their intrinsic brain architecture. This imprint might be recognizable in spatially confined intrinsic co-activity networks – at least to some degree and presumably intermixed with effects of other cognitive processes. Future studies are needed to test whether specific intrinsic domain-general networks underlie and shape CRC and CER task activations; candidates might be fronto-parietal and cingulo-opercular task-control networks, default-mode network, and ventral attention network (Kelley et al., 2015; Power et al., 2011).

4.4. Model-based mechanisms as potential common mechanism of CER and CRC

Our finding of shared neural correlates of CRC and CER is consistent with the idea of a common neurocognitive mechanism of CER and CRC. One candidate for such a shared mechanism is model-based control: Etkin and colleagues have recently transferred empirically supported concepts from reward-based learning to emotion regulation, suggesting that model-based control strategies might underlie both CER and CRC (Etkin et al., 2015). This approach provides a unifying framework for the investigation of CER and CRC, and maybe even for further distinct instances of cognitive control/self-regulation, such as cognitive task control. In concepts of model-based reward decision-making such as CRC, decisions about action selection are driven by internal models, which take into account information about stimulus value, context, short-term and long-term goals, etc. (Daw et al., 2005; Dolan and Dayan, 2013). Likewise, in CER, decisions about which emotion-regulatory action to select for achieving a desired emotional state might be guided by such a cognitive model (Etkin et al., 2015). Thus, both model-based control strategies involve decisions about actions, which alter either one's emotional state or one's craving towards consumption of a reinforcing stimulus. Our data provide empirical evidence for these theories by identifying shared neural correlates of CER and CRC, which might underlie shared mechanisms based on model-based decision-making.

Speculatively, this finding might also extend to other domains of model-based cognitive control, such as task-switching (Braver et al., 2003; Sohn et al., 2000). Coordinate-based meta-analyses of task-switching showed a consistent domain-general fronto-parietal activation pattern (Derrfuss et al., 2005; Kim et al., 2012). Moreover, another meta-analysis observed common activation in fronto-parietal cortices across a wide range of cognitive control task domains (Niendam et al., 2012). This suggests shared neural correlates for CER, CRC, and other instances of cognitive control, possibly hinting at shared neural mechanisms. Due to the problem of reverse inference, we could not conclude how many of the regions identified in this study overlap or differ from regions implicated in other functions than cognitive control. Future studies/meta-analyses are needed to address this question in more depth.

To sum up, our finding of shared neural correlates of CER and CRC provides evidence for common underlying mechanisms, which might be model-based decision-making mechanisms. However, since most included studies did not conduct task paradigms typically employed in decision-making studies, our meta-analysis cannot provide definite answers to this issue. For example, also model-free decision-making could – to a certain degree – underlie cognitive control of rewarding stimuli. Future studies are needed to further elucidate this issue by comparing CER and CRC decision-making mechanisms with a suitable task paradigm.

4.5. Limitations

The following limitations are worth noting. First, the number of included studies differed considerably between CRC (22 studies) and CER (47 studies). Such a mismatch could impact comparison analyses. Therefore, we controlled for this issue using a validated random-sampling procedure, which has already been used in several meta-analyses to deal with divergent study numbers (Crossley et al., 2014; Sha et al., 2017). Nevertheless, this problem arose due to the different research coverage of CRC and CER. Therefore, future studies in the field of CRC are needed to remove this discrepancy.

Second, studies differed with regard to demographic factors like age and gender. We also controlled for these variables by post-hoc analyses, likewise finding no disproportionate effects. However, such control analyses cannot completely rule out an influence of these variables.

Third, our meta-analytic approach is limited in testing whether both CRC and CER represent model-based decision-making. We have suggested this interpretation based on overlapping neural substrates and theoretical models (Etkin et al., 2015). But certainly, future task-fMRI studies are needed to specifically address this question by directly comparing CRC and CER, for example with model-based decision-making paradigms.

Fourth, as the majority of included studies used visual stimuli, the observed effects could be due to changes in visual processing rather than cognitive regulation itself. However, a post-hoc analysis comparing studies with and without visual stimuli suggested no significant influence of such visual processes on our results.

Fifth, as we studied cognitive regulation of craving towards rewarding stimuli, we restricted our analysis to down-regulation; future meta-analyses could study up-regulation of craving towards rewarding stimuli.

Sixth, selected CRC and CER studies used similar stimuli: CRC stimuli were emotionally engaging, and CER studies also employed pictures of disgusting food, for example. However, CRC studies only used positive stimuli, while included CER studies only used negative stimuli.

5. Conclusion

We showed a consistent brain activation pattern for cognitive reward control focused on prefrontal cortices. This pattern largely overlapped with the activation pattern of cognitive emotion regulation, but only partly with activation during response inhibition. The common activation pattern of motivational/emotional control constituted a permanently present intrinsic co-activity network, suggesting a common neurocognitive mechanism for the control of both emotion and reward.

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Conflicts of interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2019.07.008.

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