bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Greater BOLD signal during successful emotional stimulus reappraisal is associated with better dietary self-control

Abbreviated title: Emotion and dietary self-regulation

Silvia U. Maier[1,2,3], Todd A. Hare[1,2]

[1] Zurich Center for Neuroeconomics, Department of Economics, University of Zurich

[2] Neuroscience Center Zurich, University of Zurich, Swiss Federal Institute of Technology Zurich

[3] Translational Neuromodeling Unit, Institute for Biomedical Engineering, Swiss Federal Institute of Technology and University of Zurich

Author Contributions: SUM and TAH designed research, SUM performed research, SUM and TAH analyzed data and wrote the paper.

Correspondence should be addressed to:
silvia.maier@econ.uzh.ch, todd.hare@econ.uzh.ch

University of Zurich, Department of Economics,
Bluemlisalpstrasse 10, 8006 Zurich, Switzerland

This preprint is current as of February 6, 2019.

The authors confirm that the work has not been published elsewhere.

Conflict of interest

The authors declare no competing financial interests.

Acknowledgements

This work was supported by the European Union Seventh Framework Programme (FP7 grant 607310). The authors thank Astrid Dobler and Jonathan Schaffner for assistance with the data collection and organization and Jan Engelmann, Marcus Grueschow, and Susanne di Pietroantonio for advice on the experiment setup.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Abstract

We combined established emotion regulation and dietary choice tasks with fMRI to investigate behavioral and neural associations in self-regulation across the two domains in human participants. We found that increased BOLD activity during the successful reappraisal of positive and negative emotional stimuli was associated with better dietary self-control. This cross-task correlation was present in medial and lateral prefrontal cortex as well as the striatum. These results suggest that neural processes related to the reappraisal of emotional stimuli may also facilitate dietary self-control. However, within the dietary self-control task itself, we did not find that prefrontal cortex (PFC) activity significantly increased with self-control success during our food choice task, in contrast to previous reports. This prompted us to conduct exploratory analyses, which revealed that BOLD activity in PFC tracks the amount of taste and healthiness at stake on each self-control challenge trial regardless of the chosen outcome. This exploratory finding also replicated in an independent dataset. We discuss the implications of this evidence that individuals track the self-control stakes in light of theories about effortful self-regulation. In addition, we discuss features of this version of the food choice task that may have reduced the need to recruit PFC to achieve self-control. In summary, our findings indicate that the neural systems supporting emotion reappraisal can generalize to other behavioral contexts that require reevaluation to conform to the current goal.

Keywords: reappraisal, emotion, food choice, dietary self-control, fMRI

Significance statement

Reappraisal is a prominent strategy for self-regulation. Yet data to compare processes underlying the reappraisal of emotions and dietary self-control within the same individual is lacking. Here, we use two established emotion regulation and dietary choice tasks to compare both on the neural level. We found that increased BOLD activity in several brain regions including medial and lateral prefrontal cortex and striatum during the successful reappraisal of positive and negative emotional stimuli was linked to better dietary self-control. These results suggest that neural processes underlying the reappraisal of emotional stimuli may also facilitate dietary self-control.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Introduction

Cognitive strategies and, more recently, the neural mechanisms used to regulate thoughts and actions have been intensely studied in many scientific disciplines. These studies have found numerous forms of self-regulation, but one prominent strategy is the reappraisal of stimuli encountered in the world (Scherer et al., 2001; Ochsner and Gross, 2005; Etkin et al., 2015). Pioneering studies by Mischel and colleagues (Mischel et al., 1972; Mischel and Moore, 1973; Mischel and Underwood, 1974; Mischel and Baker, 1975) revealed that presenting tempting stimuli as less approachable (e.g., asking participants to imagine food stimuli as abstract pictures) increased the ability to delay gratification (see also Silvers et al. (2014)). Thus, actively reconstructing and reconsidering situations or experiences may enhance control over one's desires and emotions (Kross et al., 2005; Kross and Mischel, 2010). Converging evidence shows that reappraising stimuli decreases cravings for immediate rewards such as drugs or food (Kober et al., 2010; Hollmann et al., 2012; Hutcherson et al., 2012; Siep et al., 2012; Szasz et al., 2012; Zhao et al., 2012; Giuliani et al., 2013; Yokum and Stice, 2013; Giuliani et al., 2014; Beadman et al., 2015; Svaldi et al., 2015; Boswell et al., 2018; Garland et al., 2018; Reader et al., 2018). Overall, reappraisal appears to be a highly relevant self-regulatory skill.

As noted above, there are many forms of self-regulation in addition to explicit reappraisal. Moreover, there are still many unresolved questions about the degree to which self-regulatory processes in different laboratory tasks and real-life situations share common cognitive and neural substrates (Braver and Barch, 2002; Ridderinkhof et al., 2004; Collette et al., 2006; Dosenbach et al., 2007; Duncan, 2010; Duckworth and Kern, 2011; Heatherton and Wagner, 2011; Tabibnia et al., 2011; Ochsner et al., 2012; Duckworth and Tsukayama, 2015; Han et al., 2018; Kragel et al., 2018; Langner et al., 2018). Here, we sought to compare self-regulation in the forms of reappraisal of emotion evoking scenes and health-oriented dietary choices.

Although partially overlapping neural systems have been reported to support the reappraisal of emotions and dietary self-control, data on direct comparisons of these processes within the same individuals is lacking. Previous work looking at emotion

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

regulation has shown that explicit reappraisal recruits prefrontal cortex regions including dorsolateral prefrontal cortex (dlPFC), dorsomedial PFC (dmPFC), ventrolateral PFC (vlPFC), ventral anterior cingulate cortex (vACC), ventromedial PFC (vmPFC), and the supplementary motor area (SMA) (Gross, 1998; Ochsner and Gross, 2005; Wager et al., 2008; Ochsner et al., 2012; Buhle et al., 2014; Etkin et al., 2015; Morawetz et al., 2017a). These regions appear to modulate the reactivity of the insula and dorsal ACC, amygdala and ventral striatum (Delgado et al., 2008; Wager et al., 2008; Etkin et al., 2015; Morawetz et al., 2017b). Similarly, dietary self-control has been reported to involve a set of prefrontal regions including dlPFC, dmPFC, dACC, and vmPFC (Hare et al., 2009; Hare et al., 2011; Harris et al., 2013; Maier et al., 2015; van Meer et al., 2017). Thus, the prefrontal regions activated during emotional stimulus reappraisal and dietary self-control partially overlap. However, these regions have been reported to be involved in a wide range of behaviors beyond self-regulation, and thus it is unclear what, if any, conclusions we can draw from partially overlapping patterns of activity between emotional reappraisal and dietary choice.

In order to directly compare and contrast neural processing and regulatory success between dietary and emotional self-regulation, we tested the same individuals using both established emotion reappraisal (Ochsner et al., 2002; Wager et al., 2008) and dietary self-control tasks (Hare et al., 2009). We hypothesized that, if neural activity patterns during the reappraisal of emotional scenes are relevant to or correlated with processes that aid dietary self-control, then individual differences in BOLD activity during successful reappraisal will be associated with success in the dietary self-control task or vice versa.

Materials and Methods

Participants

Forty-three healthy adults (18 men) participated in this study. All participants were German native speakers and maintained a health-oriented lifestyle (including a

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

specific interest in healthy eating), but also enjoyed eating snack foods (e.g. chocolate, cake, cookies, chips or crackers) and did so on at least two occasions per week. We used the Beck Depression Inventory I (Beck et al., 1978), German validated version by Hautzinger et al. (1995), and Toronto Alexithymia Scale (Bagby et al., 1994), German validated version by Franz et al. (2008), to screen for depression and emotion blindness because both conditions have been associated with altered emotion perception. All participants provided written informed consent at the day of the experiment according to the Declaration of Helsinki, and the study was conducted in accordance with the regulations of the Ethics Committee of the Canton of Zurich.

Five participants had to be excluded from dietary self-control analyses: two did not complete this task, for one the experiment could not be constructed with a sufficient number of challenging trials, one did not comply with the instructions, and one never chose to eat during the self-control challenge trials. This left a sample of 17 men (mean age = 22.47 ± 2.27 SD years; BMI mean = 22.76 ± 2.34 SD) and 21 women (mean age = 21.5 ± 2.09 SD years; BMI mean = 21.10 ± 2.25 SD) for the behavioral analyses of dietary choices. One additional participant had to be excluded from the fMRI dietary choice analyses for excessive head motion, but this dataset was included in the behavioral analyses. Seven participants were excluded from reappraisal analyses: five fell asleep during a substantial portion of the task (detected by the eye-tracker), one deliberately closed the eyes during negative pictures (reported during debriefing), and one reported experiencing discomfort due to head positioning during the task. We reasoned that the participant who was uncomfortable, but remained in the scanner without complaint until after the study was engaging in constant self-regulation that would interfere with our analyses. One additional woman was excluded from fMRI analyses for this task due to excessive head motion. This left 35 usable fMRI datasets for the reappraisal task and 37 for the dietary self-control task. In total 31 participants (17 women) completed the reappraisal and dietary self-control tasks and had good fMRI data quality during both.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Procedure

Initially, a 6-minute baseline heartbeat measurement was taken while participants were lying supine in a comfortable position in a quiet room. Participants then rated a set of 180 foods for taste (regardless of healthfulness) and health (regardless of taste) on a continuous visual analog scale with anchors in steps of 1 from -5 to +5 (with -5 being not at all, and +5 being maximally healthy / tasty), or vice versa. The middle of the scale showed a zone that was termed “neutral” and comprised the area that corresponded to -5 and +5% of the total scale length centered on zero (Figure 1A). We randomly determined whether participants would use a rating scale in which the left-right orientation ranged from negative to positive, or positive to negative. We ensured that individual participants rated food properties and later feelings using the same directionality.

Next, participants received a short training session for the dietary self-control task. At the start, they were reminded to try and choose healthier foods as often as they could, before they made 5 practice choices to get accustomed to the choice screen. The experimenter then introduced the Self-Assessment Manikin (SAM) Scale for rating current emotions according to the procedure detailed in Lang et al. (1999) and explained the reappraisal task using a standardized instruction sheet with one example for positive and negative pictures. Participants were instructed to practice down-regulating their feelings elicited by both negative and positive pictures from the International Affective Picture System by Lang and colleagues. In the *view* condition, they were instructed to watch the presented image and become aware of the feelings that this image evokes. They should not try to alter these feelings. In the *reappraisal* condition, participants should watch the image and try to come up with a different story that could explain the scene, such that the evoked feeling becomes weaker. Negative feelings should become less negative, and positive feelings less positive. For example, one could think of the image as a scene or mock-up from a movie: Things are not as bad or good as they seem, but just staged.

Participants then trained with a computerized version of the task as it was presented in the fMRI scanner, first for 2 pictures with free timing, and then for 2 pictures with

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

the timing for picture presentation and emotion rating that was applied during the scan.

In the scanner, participants completed the dietary self-control task and emotion regulation task each in a single run with 100 trials, in cross-balanced order. After the first run, the anatomical scan was collected to allow for a washout period of 7 minutes between the tasks.

In the dietary self-control task (Figure 1B), participants were shown one food in the center of the screen on each trial, and had to indicate within the 3-second response window whether they wanted to eat this food or nothing at the end of the study. Choices were customized such that each participant would face approximately 75 percent challenging choices, in which the presented food was either i) tastier and less healthy than neutral, or ii) healthier and less tasty than neutral. In the remaining choices, health and taste were aligned, so the food was tastier and healthier, or less tasty and less healthy than neutral. Trial types were randomly intermixed, and a jittered inter-trial interval (uniform draw of 2 to 6 seconds) separated each trial.
In the emotion regulation task (Figure 1C), before each block of 20 trials, the condition “view” or “reappraise” was displayed for 1 second. Participants then saw a scrambled version of the stimulus image for 1 second centered on the screen before the stimulus was displayed in the same spot for 7 seconds. During this time, participants had to either passively view the image without altering their feelings, or reappraise their feeling according to the trained procedure so that their feelings became weaker. To remind them of the condition to be applied, a shortened cue (“V” for view or “R” for “reappraise”) replaced the fixation cross on top of the stimulus. We omitted the letters in the figure for clarity. Participants then had 4 seconds to rate their current feeling on a 9-point SAM valence scale. A jittered inter-trial interval (uniformly sampled from 1 to 5 seconds) separated one trial from the next.

Block types (Reappraise Positive, Reappraise Negative, View Positive, View Negative, View Neutral) were presented in 5 different orders that were pseudo-randomized

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

across participants. Each block was followed by a 15-second break (with the word "pause" appearing over a countdown that showed the remaining seconds of break time).

IAPS Stimuli were selected based on a validation study in a German-speaking sample of young adults (Grühn and Scheibe, 2008). Based on the mean ratings given by young adults in this dataset, we identified 40 images that scored highest on positive and 40 images that scored highest on negative valence, skipping any that showed foods, and proceeding to the next best-scoring images as a replacement. We distributed the positive and negative images each into two sets such that both sets in each domain were equated on average for arousal (mean negative: 6.99 ± 0.44; mean positive: 2.86 ± 0.43 based on the ratings of the sample in Grühn and Scheibe (2008)). We randomly allocated for each of our participants which set they would see in the "view" and "reappraise" condition. We then identified 20 images that scored neutral on both valence and arousal.

After the MRI scans, participants re-rated all 40 stimuli that had been presented in the reappraisal conditions while sitting at a standard computer terminal. Participants were asked to rate the images as in the "viewing" condition, i.e. rating the feeling elicited by the image without altering this emotion.

Lastly, there was a 30-minute waiting period during which one of their food choices was realized and, if chosen, eaten. Participants also filled in a battery of psychometric questionnaires during this waiting period. At the end of the 30 minutes, participants were paid a flat fee of 90 CHF for their participation in this 3-hour study.

Psychometric inventories

The psychometric questionnaire battery included the Three Factor Eating Questionnaire, Dutch Eating Behavior Questionnaire, PANAS (to describe their mood for the last week), BIS-BAS, BIS-15 (German validated version of the BIS-11), and NEO-FFI.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

fMRI data acquisition

The MRI data were recorded using a Philips Achieva 3 T whole-body scanner with an eight-channel sensitivity encoding head coil (Philips Medical Systems). Stimuli were presented with the Psychophysical Toolbox Software (Psychtoolbox 3.0, Brainard (1997), RRID:SCR_002881) via back-projection to a mirror mounted on the head coil.

We acquired gradient echo T2*-weighted echo-planar images (EPIs) with blood-oxygen-level-dependent (BOLD) contrast (37 slices per volume, Field of View 200 x 132.6 x 200 mm, slice thickness 3 mm, 0.6 mm gap, in-plane resolution 2.5*2.5 mm, matrix 80*79, repetition time 2344 ms, echo time 30 ms, flip angle 77°) and a SENSE reduction (i.e. acceleration) factor of 1.5. Volumes were acquired in axial orientation. We collected 354 volumes during the dietary choice run, and 679 volumes during the emotion regulation run. Both runs were collected in ascending order. Before each run, five “dummy” volumes were collected to allow for stabilization of the magnetic field. A T1-weighted turbo field echo structural image was acquired in sagittal orientation for each participant between the functional scans (181 slices, Field of View 256 x 256 x 181 mm, slice thickness 1 mm, no gap, in-plane resolution 1*1 mm, matrix 256*256, repetition time 8.3 ms, echo time 3.89 ms, flip angle 8°). To measure the homogeneity of the magnetic field we collected B0/B1 maps before the first run and before acquiring the structural scan (short echo time = 4.29 ms, long echo time = 7.4 ms). We measured breathing frequency and took an electrocardiogram with the in-built system of the scanner in order to correct for physiological noise.

fMRI preprocessing

Functional data were spatially realigned and unwarped with statistical parametric mapping software (SPM12, Update Rev. Nr. 6906; Functional Imaging Laboratory, University College London, RRID:SCR_007037), slice-timing corrected, coregistered to the participant’s T1-weighted high resolution structural image and normalized to

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

the individual mean EPI template before segmenting according to the individual T1 scan and smoothing with an isometric Gaussian kernel (4 mm full width at half maximum). In order to account for fluctuations in the BOLD signal due to physiological noise, we finally used RETROICOR as implemented in the TAPAS PhysIO toolbox (Version 2015; open source code available as part of the TAPAS software collection: http://translationalneuromodeling.org/tapas/) by Kasper et al. (2017) to model respiration and heartbeat (Glover et al., 2000; Hutton et al., 2011). Following Harvey et al. (2008), the algorithm implemented in the PhysIO toolbox uses Fourier expansions of different order to the estimate the phases of cardiac pulsation (3rd order), respiration (4th order) and cardio-respiratory interactions (1st order).

Experimental Design and Statistical Analysis

We sought to identify whether neural processes occurring during reappraisal were associated with the behavioral outcome of another, distinct self-regulation task: dietary self-control. All correlations reported in this paper were calculated using a Bayesian estimation procedure (Kruschke, 2015), where we calculated the Bayesian equivalent of Pearson's (linear) or Spearman's (rank) correlation coefficients and mean squared error (MSE) across all participants.

Our hypothesis was that neural activity during reappraisal would be correlated with dietary self-control success, and potentially vice versa. Note, however, that these two relationships are distinct and a relationship in one case does not indicate or require the other. To compare both reappraisal and dietary self-control abilities, we chose a within-subject design. Based on prior reports of these self-regulation tasks in the literature, we expected a moderate effect size (as reported in Webb et al. (2012)).

All behavioral analyses presented in this paper were performed with the R ("R Core Team," 2015), version 3.5.1, RRID:SCR_001905, STAN (Carpenter et al., 2016) and JAGS (Plummer, 2003) statistical software packages. For all Bayesian modeling analyses, we used the default, uninformative priors specified by the brms (Bürkner,

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

2017) and BEST (Kruschke, 2013, 2015) R-packages. SPM12 (Penny et al. (2006), update 6906) was used to preprocess fMRI data and calculate first-level models. FSL's Randomise tool (Winkler et al., 2014) was used to run nonparametric permutation tests (n = 5000 permutations) with threshold-free cluster enhancement (TFCE) on the group level. We chose to switch to the implementation in FSL 5 (RRID:SCR_002823) for this analysis, because the TFCE and permutation algorithms were more fully documented and computed faster in FSL compared to SPM12. Figures 4 to 7 were created using the MRIcron and MRIcroGL software packages (http://www.mccauslandcenter.sc.edu/mricro/mricron/, http://www.mccauslandcenter.sc.edu/mricro/mricrogl/, RRID:SCR_002403). Anatomical labels for the tables were derived from the Harvard-Oxford cortical and subcortical atlases (Desikan et al., 2006, RRID:SCR_001476) with FSL's atlasquery and cluster commands.

In the main text we report T and p values for the strongest contiguous cluster in each analysis. Exact T values at the voxel-level can be found in a Neurovault repository (link: https://www.neurovault.org/collections/YPGQPMUT/). For non-significant contrasts we report the minimum whole-brain corrected p-values (or minimum small-volume corrected p-values where indicated). All analysis code and raw data for the behavioral results can be found at https://github.com/silvia-maier/Maier_Hare_Emotion_and_dietary_selfregulation. Raw fMRI data will be accessible after publication on https://openneuro.org.

Behavioral Analyses

In the emotion paradigm, reappraisal success was measured as the difference between emotion ratings given when reappraising the image inside the scanner and post-scan ratings made when viewing the same picture again without reappraising it as in Ochsner et al. (2002). We calculated success scores for negative-valence stimuli as the difference, Reappraisal minus View, because the reappraised rating should be higher (i.e. more positive) than the unregulated viewing rating if reappraisal of negative stimuli was successful. The difference, View minus Reappraise, was

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

calculated for positive reappraisal trials, because for positive stimuli the unregulated View ratings should be higher than the reappraised rating when successfully modulating positive emotions. Our primary measure of reappraisal success was computed across both negative and positive images. However, we also computed and checked the reappraisal success scores for each valence separately in some cases noted below.

To test whether ratings differed significantly between the conditions, we conducted the following linear regression:

(Eq. 1) Valence rating = $\beta_0 + \beta_1$ condition + ε

In this model, *valence rating* was the rating given on the respective trial, coded from 1 (very sad) to 9 (very happy) in steps of 1, according to the Self-Assessment Manikin scale, and *condition* was a factor with 5 levels (0 = neutral view, 1 = negative view, 2 = negative reappraisal, 3 = positive reappraisal, 4 = positive view). The model included subject-specific random intercepts and slopes for the condition.

In the dietary self-control paradigm, challenging trials were defined as those trials in which health and taste attributes were not aligned. Self-control success was measured as the proportion of all challenging trials in which participants refused to eat a tasty, unhealthy food, or accepted eating a healthy, unpalatable food as in Hare et al. (2009). We attempted to tailor each participant's food choice set such that s/he would face 75 self-control challenges (in which health and taste were not aligned) out of 100 decisions. The number and types of challenges we could present each individual depended on their ratings for the full set of 180 foods. Most participants faced more self-control challenges for items that were unhealthy and tasty (out of 100 choices: minimum 14, median 52.5, maximum 77) than challenges including healthy but unpalatable items (minimum 0, median 15, maximum 46).

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

To characterize dietary choice patterns, we modeled participant's choices of the healthier item as a function of taste and health properties with a Bayesian mixed logistic regression model (Eq. 2):

(Eq. 2) Yes = β_0+ β_1 taste + β_2 health
+ β_3 order + β_4 hunger + β_5 gender + β_6 BMI + β_7 RE
+ β_8 taste x order + β_9 health x order + ε

In this model, *Yes* was a binary indicator for choices taking the value 1 when the participant chose to eat the presented item and 0 otherwise, and *taste* and *health* denoted the respective ratings for the item depicted on the screen that were standardized and mean-centered across all participants. The model included subject-specific random intercepts and subject-specific random slopes for the *taste* and *health* attributes*,* allowing both variables to have differential effects in each participant. To check the robustness of our results, we also included control variables for the main effect of the *order* in which reappraisal and dietary self-control tasks were performed and the interactions of task order and taste and health attributes, as well as the main effects of *hunger* level (in percent, indicated on a visual analog scale from 0, not at all, to 100, maximally hungry), *gender* (male / female, self-reported), Body Mass Index (*BMI*) and restrained eating score (*RE*) on the restraint subscale of the Three Factor Eating Questionnaire (Pudel and Westenhöfer, 1989). Task order and gender were modeled as factors, and standardized scores were used for eating restraint, BMI and hunger level.
To test for the determinants of self-control in challenging trials, in which health and taste aspects were not aligned, we modeled self-control success as a function of taste, health and challenge type:

(Eq. 3) SCS = β_0+ β_1 Taste + β_2 Health + β_3 LTHH
+ β_4 Taste * LTHH + β_2 Health * LTHH + ε

Where *SCS* was a binary variable taking the value of 1 if participants succeeded on this trial and 0 if they did not, *Taste* and *Health* described the within-participant z-

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

scored taste and health ratings for the depicted food, and *LTHH* was a factor with two levels (coded as 1 if participants saw a low-taste/high-health food on this trial and 0 otherwise, i.e. using high-taste/low health challenges as reference). The model included subject-specific random intercepts and subject-specific random slopes for taste, health, challenge type and their interactions.

To test for reaction time differences as a function of trial type, we fit the model described in Eq. 4:

(Eq. 4) $\log(rt) = \beta_0 + \beta_1 \text{ Yes} + \beta_2 \text{ Type} + \beta_3 \text{ (Yes x Type)} + \varepsilon$

where *log(rt)* was the log-transformed reaction time (rt) for food choices on each trial, *Yes* was a binary indicator for the choice made, equaling 1 if the participant chose to eat the item on the screen and 0 otherwise, and *Type* was a factor with three levels indicating the type of trial (0 = no challenge trials, 1 = challenge trials with high-taste/low-health (HTLH) foods, and 2 = challenge trials with low-taste/high-health (LTHH) foods). The model included subject-specific random intercepts and subject-specific random slopes for answer, trial type and their interaction.

Inspecting the results of fMRI model GLM-SCS (described below) prompted us to investigate more carefully how individuals solved self-control challenges. To this end, we performed an exploratory analysis to investigate how participants tracked the objective challenge and importance of self-control choices. We constructed a measure we call the self-control *stakes* (see Figure 7A, upper left and lower right quadrant). The stakes variable is a combination of the absolute magnitudes of two food attributes: One is the taste of the food, which determines how much taste temptation participants have to resist, or how much aversion they have to overcome in order to eat an unpalatable item. The other, separate aspect is the health benefit or cost they accrue in doing so. The stakes are high both when a very tasty temptation carries with it large health drawbacks (upper left quadrant) and when a highly unpalatable food would yield high health benefits (lower right quadrant). By

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

definition, self-control is only required when the taste and healthiness attributes are in opposition and, therefore, the stakes are zero throughout both the lower left and upper right quadrants. In our analyses, we compute what is at stake in each self-control challenge trial by adding up the absolute value (i.e., the distance from zero, which is in our case equals neutral on the rating scale) of the taste (tr) and health (hr) aspects for all foods in the upper left or lower right quadrants of Fig. 7A:

(Eq. 5) self-control stakes = $|tr| + |hr|$

Note that this measure is different from subjective difficulty or decision conflict, which increases the closer weighted taste and health values are to zero (Fig. 7B). We calculated the subjective difficulty or decision conflict on each trial according to equation 4:

(Eq. 6) decision conflict = $|\text{weighted tr} + \text{weighted hr}| * -1$

We also sought to estimate the weights on taste and health ratings that capture the subjective importance of taste and health aspects to the decision maker for use in our fMRI analyses. We estimated these weights using the logistic regression model described in Eq. 7 that was calculated for each participant:

(Eq. 7) Yes = $\beta_0 + \beta_1$ taste + β_2 health + ε

Similar to the model in Eq. 2, *Yes* was a binary indicator for choices taking the value 1 when the participant chose to eat the presented item and 0 otherwise, and *taste* and *health* denoted the respective ratings for the item depicted on the screen that were mean-centered before entering the regression.

fMRI analyses

General linear models. All fMRI models included nuisance regressors for head-motion and cardiac and respiratory effects on each trial. Additionally, in case motion exceeded 2 mm or 2 degrees tilt, a binary regressor flagged this trial, the three

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

preceding trials and one subsequent trial to account for any variance associated with the excessive motion. In total, 12 out of 35 included emotion reappraisal datasets contained flagged volumes (mean = 3.7%, range = [0.7%; 14.1%] of all acquired volumes), and 2 out of 37 included dietary choice datasets (mean = 7.2%, range = [1.4%; 13%]).

In the fMRI models of the dietary self-control task, regressors were defined as boxcar functions with durations equaling the reaction time on each trial. In the model of the emotion reappraisal task, onsets for the cue and reappraisal/view screens were modeled as boxcar functions with a duration equaling the cue depiction and task periods (1 and 7 seconds), and rating periods were modeled as boxcar functions with durations equaling the reaction time for the rating.

Dietary self-control task. To assess neural activity during dietary choice, we first calculated GLM-FC (food choice). It modeled events of interest for all trials in which a choice was made. The model included parametric modulators for the subjective food value (linear and quadratic effects), which were orthogonalized. We calculated participant-level and group-level contrasts for the parametric effects of subjective food value.

Subjective food value was calculated as in Maier et al. (2015) and Maier and Hare (2017): We first estimated the logistic regression model specified in Eq. 7 for each participant to model their food choices as a function of taste and health ratings. We then used these taste and health weights that characterize the subjective importance the participant placed on taste and health aspects to weight taste and health ratings for the food choices on each trial and summed up the weighted taste and health values into an overall subjective food value on each trial.

In order to track taste and health aspects separately, we next calculated GLM-TH (taste/health). It modeled events of interest for all trials in which a choice was made. The model included parametric modulators for the taste and health ratings (linear

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

effects), which were not orthogonalized. We calculated participant-level and group-level contrasts for the parametric effects of taste and health.

We calculated a further GLM to test if any brain regions showed differential activity during self-control success versus failure (GLM-SCS), and an exploratory GLM to test whether the brain tracked the stakes of engaging self-control from trial to trial (GLM-ST).

GLM-SCS was constructed after Hare et al. (2009). It modeled events of interest for (1) Self-control success, (2) Self-control failure, (3) Trials without a self-control challenge, and (4) Missed trials. None of these regressors had parametric modulators. Following the analysis of Hare and colleagues, we calculated a second-level correlation of individual self-control success level with the Self-control Success > No Challenge contrast to track individual differences in the BOLD signal relating to differences in self-control usage. To test for a link with individual differences in emotion reappraisal success, we additionally calculated a correlation of the Self-control success > No challenge contrast with the overall emotion reappraisal success score. Lastly, we also calculated the contrast for Self-control Success > Failure on the individual and group level.

The exploratory model GLM-ST tests for brain areas correlating with our novel measure of self-control *stakes*, which should be represented in self-control challenges regardless whether or not participants succeeded in using self-control (see Figure 7A, upper left and lower right quadrant). To examine our neural data, we used the stakes measure in addition to decision conflict as parametric modulators in GLM-ST. This GLM included onsets for (1) all trials in which participants decided on palatable-unhealthy or unpalatable-healthy items, (2) palatable-healthy or unpalatable-unhealthy foods, and (3) missed trials. The “stakes” modulator was orthogonalized with respect to decision conflict in order to obtain a readout of the unique signal associated with the need for self-control beyond that correlated with decision conflict (Mumford et al., 2015). The modulator thus explained unique variance for self-control need, adjusted for the variance explained by decision

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

conflict and the variance shared between both. We calculated participant- and group-level contrasts for the stakes parametric modulator in the challenging trials. Note that this model contained also second-order expansions for the parametric modulators in order to control for non-linear effects, but these did not explain any variance, indicating only linear effects were present.

To validate our novel stakes measure, we also re-analyzed a previously acquired dataset with GLM-ST. For the description of this dataset please see our prior reports in Maier et al. (2015) and Maier and Hare (2017). GLM-ST was run including all 51 participants. Note that in this replication test, we only included first-order polynomial expansions in the model given that there were no second-order effects in the original dataset. Here, we only evaluated the group-level representation of the stakes measure.

Reappraisal task. Our main general linear model on emotion regulation (GLM-ER) tested for BOLD activity correlated with stimulus reappraisal. GLM-ER modeled events of interest for (1) positive view, (2) positive reappraisal success, (3) positive reappraisal failure, (4) negative view, (5) negative reappraisal success, (6) negative reappraisal failure, (7) neutral view trials, as well as (8) the time during which participants gave their emotion ratings. None of these had any parametric modulators. We calculated a first-level contrast for reappraisal success subtracting BOLD activity during viewing, collapsed over positive and negative modalities. On the group level, we then examined with this contrast whether we detected increases in BOLD activity during Reappraisal Success compared to Viewing, and whether these differential increases for each participant correlated with their dietary self-control success score. In addition, to test whether BOLD activity differed for the success in negative compared to positive regulation trials, we calculated the contrasts Positive Reappraisal Success > Negative Reappraisal Success and Negative Reappraisal Success > Positive Reappraisal Success on the individual and group level.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

We conducted two analyses examining associations between BOLD activity and performance across tasks. Therefore, we applied a Bonferroni-correction to the results resulting in a significance threshold of $p < 0.025$ for our whole brain analysis. We also conducted a region of interest (ROI) analysis in five regions that have previously been found to be involved in reappraisal processes as well as decision-making (amygdala, dlPFC, hippocampus, striatum, vmPFC) to test whether activity change there in reappraisal success compared to viewing stimuli related to self-control success in the dietary domain. We used a Bonferroni-correction to account for testing in 5 separate regions (resulting significance threshold = $p < 0.01$).

Results

Behavior

Behavioral results within each separate task

We found that participants were able to both regulate their emotions and use dietary self-control to select healthier foods within each separate experimental task. In the emotion regulation task, we asked participants to either 1) simply view and react naturally, or 2) reappraise photographs with different emotional valence. After seeing or reappraising the pictures for seven seconds, they rated their current affective state using the SAM scale on which 1 indicated the most negative and 9 the most positive emotional valence (Figure 2). To test whether our paradigm was effective, we estimated a Bayesian linear regression that modeled emotion ratings as a function of block type (see Eq. 1 and Table 1). Ratings after reappraising negative content were more positive (mean negative reappraise rating = 4.25 ± 0.81 SD, Posterior Probability of Negative Regulate being greater than Negative View ratings (PP(Negative Regulate > Negative View Ratings)) > 0.9999) than after simply viewing negative scenes (mean negative view rating = 2.69 ± 0.54 SD; PP(Neutral View > Negative View Ratings) > 0.9999). Likewise, emotion ratings after reappraising positive stimuli (mean positive reappraise rating = 5.21 ± 0.9 SD; PP(Positive Regulate < Positive View Ratings) > 0.9999) were lower than after simply viewing positive content (mean positive view rating = 7.09 ± 0.67 SD; (PP(Positive View >

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Neutral View Ratings) > 0.9999)). Thus, participants were successful in regulating their emotional responses to the affective pictures when asked to do so.

In addition to the emotion regulation task, participants also completed a food choice task. The food choice task required subjects to make 100 decisions about whether or not they would eat the food item shown on the screen after the MRI scan. Participants knew that one of these trials would be selected at random and their choice on that trial implemented for real, meaning that they would have to eat the food item or go hungry for an additional 30 minutes. In analyzing the food choice behavior, we first examined the entire set of food choices using a mixed-effects logistic regression (see Eq. 2 and Table 2). This regression showed that participants considered both taste and health when choosing whether or not to eat the item shown on the screen (regression coefficient (coef.) taste = 1.47 ± 0.22, HDI = [1.04; 1.93]; coef. health: 1.46 ± 0.27, HDI = [0.95; 2.00]). Consumption choices did not significantly differ as a function of task order, hunger levels, gender, BMI or restrained eating score (see Table 2).

Next, we focused specifically on food choices that represented a self-control challenge. These were trials in which the food was either palatable, but unhealthy, or healthy, but unpalatable according to the participants' subjective ratings for healthiness and tastiness. Participants faced a self-control challenge on approximately 75 out of the 100 trials. The mean dietary self-control success rate across all participants was 62 ± 27 SD %. This indicates that self-control success rates were high on average, but also that there was substantial variability across participants in dietary self-control. We also found that self-control success was achieved more often by refusing to eat tasty-unhealthy foods (Figure 3A). The mean self-control success rate for refusing the tasty-unhealthy foods was 77% in our sample, whereas the mean success rate for accepting unpalatable-healthy foods was only 19%.

To test the influences of taste and health attributes and challenge type on self-control success, we performed a second mixed effects logistic regression (Eq. 3 and

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 3). Overall, the log odds of self-control success were lower for unpalatable-healthy foods (coef. = -1.89 ± 0.91 SD, 95% Highest Density Interval: [-3.77; -0.17]) compared to tasty-unhealthy foods. For tasty-unhealthy food, higher taste decreased the log odds of success (coef. = -1.40 ± 0.33 SD, 95% HDI: [-2.04; -0.72]). Higher health ratings of the tasty-unhealthy foods also decreased the chances of refusing to eat them (coef. = -2.75 ± 0.44 SD, 95% HDI= [-3.67; -1.94]), perhaps because choosing such a food with relatively higher healthiness might be perceived as a less serious failure. For healthy-unpalatable food, relatively less bad-tasting foods increased the log odds of success (coef. = 2.67 ± 0.58 SD, 95% HDI= [1.63; 3.93]). However, healthiness had little influence on choice during healthy-unpalatable trials. Note that the total effect is equal to the Type x Health interaction coefficient (2.69) added to the baseline coefficient (-2.75). In other words, the significant influence of healthiness during unhealthy-palatable trials, which serve as the baseline in our regression, disappears (2.69 + -2.75 = -0.06) in healthy-unpalatable self-control challenges. The reduced influence of healthiness on these trials may be because the alternative of eating nothing at all for an extra 30 minutes is not viewed as an unhealthy outcome.

We also examined reaction times (RT) for trials including healthy-unpalatable and palatable-unhealthy foods as well as trials in which taste and health attributes were aligned (Figure 3B). Notably, participants were faster to refuse high-taste/low-health foods (mean = 1.10 ± 0.07 SEM seconds) compared to accepting high-taste/high-health foods (mean = 1.22 ± 0.07 sec), and fastest to refuse low-taste/low-health foods (mean = 1.04 ± 0.06 sec; see Eq. 4 and Table 4). These RT results suggest that participants may have developed a bias toward refusing to eat the foods. This bias is potentially strategic for self-control because they most often saw unhealthy foods and, therefore, may have prepared in advance to decline eating the foods.

Testing behavioral associations between tasks

Next, in order to address our questions about the potential link between emotional reappraisal and dietary self-control at the behavioral level, we tested for an association between the self-reported reappraisal and dietary self-control success

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

scores. However, we did not observe a significant correlation between overall dietary self-control and emotional reappraisal success (Bayesian rank correlation rho = -0.023, 95% Highest Density Interval (HDI) = [-0.368; 0.306], posterior probability of rho greater than zero (PP rho > 0) = 0.450). For completeness, we also ran separate tests for reappraisal success in the positive (rho = 0.136, 95% HDI = [-0.199; 0.472], (PP rho > 0) = 0.781) and negative valence domains (rho = -0.175, 95% HDI = [-0.499; 0.156], (PP rho > 0) = 0.159), but these did not show significant correlations with dietary self-control either.

fMRI

Testing for previously observed patterns of BOLD activity within each task

Before testing for associations between dietary self-control and emotion regulation at the neural level, we first checked if the patterns of neural activity within each paradigm were consistent with previous findings from emotion reappraisal and dietary choice studies.

Our findings from the reappraisal paradigm were consistent with past fMRI studies examining the neural correlates of reappraising emotional scenes. The contrast of Reappraisal Success > View across both positive and negative valence showed several regions noted in previous work (Gross, 1998; Ochsner and Gross, 2005; Wager et al., 2008; Ochsner et al., 2012; Buhle et al., 2014; Etkin et al., 2015; Morawetz et al., 2017a) such as medial temporal gyrus, SMA, caudate, putamen, insula, vlPFC and dlPFC were more active when reappraising emotional scenes compared to viewing them and reacting naturally (GLM-ER; Figure 4, Table 5). In line with the behavioral finding that participants succeeded in reappraising both valences, positive and negative emotion reappraisal success did not significantly differ in terms of BOLD activity (Negative Reappraisal Success > Positive Reappraisal Success: all p-values > 0.28, whole-brain family-wise error corrected; Positive Reappraisal Success > Negative Reappraisal Success: all p-values > 0.29 whole-brain corrected).

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

In the food choice task, some of our analyses were consistent with previous reports, but in other cases there were interesting differences. Using GLM-FC, we found BOLD activity scaling with subjective food value in a set of brain regions typically associated with value-based choices during tests of self-control (Hare et al., 2009; Hare et al., 2011; Enax et al., 2015; Maier et al., 2015; Spetter et al., 2017; van Meer et al., 2017) and more generally (i.e. without explicit self-control) (Bartra et al., 2013; Clithero and Rangel, 2013). These included the medial prefrontal and posterior cingulate cortices (Figure 5A, Table 6; $p = 0.01$, whole-brain corrected). A separate GLM (GLM-TH) that replaced the subjective food values with the individual taste and healthiness ratings showed that overlapping regions also represented healthiness (Figure 5B, Table 7; $p < 0.0001$) and tastiness (Figure 5C, Table 8; $p = 0.02$) attributes. Figure 5D depicts the overlap between the regions that significantly encoded subjective food value as well as taste and health separately (conjunction threshold = $p < 0.05$, whole-brain corrected for family-wise error).

Previous studies have reported that self-control success is associated with greater activity in the dorsolateral prefrontal and occipital cortex (Hare et al., 2009; Christakou et al., 2011; Crockett et al., 2013; Harris et al., 2013; Drobetz et al., 2014; Schonberg et al., 2014; Decker et al., 2015; Luerssen et al., 2015; Maier et al., 2015; Hill et al., 2017; Spetter et al., 2017; Baumeister et al., 2018; Bertsch et al., 2018; Jimura et al., 2018; Lee et al., 2018; Schmidt et al., 2018; Shahbabaie et al., 2018; Sheffer et al., 2018). However, in the current dataset, we did not find greater activity in the dlPFC, or any other brain regions, on Successful Self-control trials compared to Self-control Failures (all p-values > 0.21, whole-brain corrected; all $p > 0.65$ small-volume corrected in left lateral PFC). Similarly, the contrast for Self-control Success > No Challenge yielded no significant result in the prefrontal cortex (all p-values > 0.37, whole-brain corrected; all $p > 0.77$, small-volume corrected in left lateral PFC). Individual differences in self-control success did not correlate with activity in any prefrontal regions, but we did find that greater activity within the left lingual and fusiform gyri ($p = 0.01$, whole-brain corrected) during Self-control Success vs. No Challenge trials was positively correlated with individual dietary success rates. These

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

results linking self-control to activity in regions involved in visual and object processing is consistent with both the speculations about early filtering of visual attention as a mechanism to facilitate self-control in Harris et al. (2013) and the pattern of fast refusals for unhealthy foods observed in the current participants' behavior.

BOLD activity during emotion reappraisal is associated with dietary self-control success

Next, we tested the hypotheses that neural activity patterns during successful reappraisal would be related to individual differences in dietary self-control success or vice versa. We computed a between-subjects regression relating individual differences in dietary self-control to voxel-wise differences in the Reappraisal Success > View contrast. This analysis revealed that participants whose BOLD signal changed more strongly when successfully reappraising compared to viewing emotional content were also better at dietary self-control (Figure 6A, Table 9; $p < 0.025$ whole-brain corrected).

We additionally conducted a number of a-priori region-of-interest (ROI) analyses in regions that have previously been associated with reappraisal and self-control decisions. We computed Pearson's correlation coefficient between dietary self-control success and Reappraisal Success > View BOLD activity from the following regions (bilateral, anatomically defined based on the Harvard-Oxford Atlas): amygdala, hippocampus, striatum (nucleus accumbens, caudate and putamen) and vmPFC as well as left dlPFC (from the union of voxels associated with self-control in Hare et al. (2009) or Maier et al. 2015). We identified positive correlations between the contrast of Reappraisal Success > View and dietary self-control success in vmPFC, hippocampus and striatum (Bonferroni-corrected for multiple comparisons: all p-values < 0.01; see Figure 6B).

The complementary test for whether BOLD activity differences in the dietary Self-control Success > No Challenge contrast from GLM-SCS were linked to overall emotion reappraisal success scores did not yield a significant correlation in any

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

regions (all p-values > 0.35 after whole-brain correction). Potential reasons for this asymmetry in the relationship between BOLD activity and regulation success across domains are considered in the Discussion section.

Prefrontal cortex BOLD signals correlate with dietary self-control stakes

Both the unexpected tendency to quickly refuse palatable and unpalatable food items and the lack of a significant relationship between PFC activity and dietary self-control prompted us to conduct additional exploratory analyses on the fMRI data from the food choice task. One question we had was if participants were tracking the healthiness and tastiness attributes at stake on each trial with regard to the need for self-control even though they seemed to have a bias toward declining to eat the food items. Given the previous findings implicating left PFC in dietary self-control cited above, we initially searched there. We found that a measure of the objective self-control stakes (defined as |HR| + |TR| on challenge trials, see GLM-ST) was correlated with BOLD signals in left Inferior Frontal Gyrus (IFG) during dietary decisions (Figure 7C, blue areas; peak MNI coordinate = [-45 29 0], max T = 5.23, p = 0.01, svc within left prefrontal cortex). A post-hoc comparison of the average coefficients for taste and healthiness stakes (i.e. |TR| or |HR|) within this functional ROI indicated that the left IFG region represented both attributes, rather than tracking only one or the other. Lastly, a whole-brain analysis revealed a trend for a bilateral activation of the IFG (with additional activation in the right IFG: peak MNI coordinate = [55 29 0], max T = 5.49, p = 0.06 whole-brain corrected), suggesting that this pattern is not strictly lateralized. Thus, this initial set of exploratory analyses indicated that the BOLD activity in the IFG is correlated with the size of the stakes for self-control challenges.

In order to test whether the correlation between IFG activity and self-control stakes could be replicated in another independent dataset, we went back to the food choice and fMRI dataset first reported in Maier et al. (2015). We estimated the same BOLD GLM (i.e. GLM-ST) on these data, and found that indeed, the BOLD signal during challenging trials tracked the stakes in this independent dataset as well. Using the same left lateral prefrontal cortex mask as a small-volume search space, we

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

observed activity in a region of the IFG that overlapped with the results from the current study (Figure 7C, purple areas represent overlap between current and prior datasets), as well as the medial PFC (Figure 7C, red areas; Table 10A; $p < 0.0001$ svc within left prefrontal cortex). A whole-brain analysis of the Maier et al. (2015) dataset revealed activity tracking the stakes in a large set of bilateral prefrontal voxels in the medial frontal gyrus, Brodmann areas 9 and 10, anterior cingulate, Brodmann areas 8 and 32 as well as the supplementary motor area (Table 10B). These results show that BOLD activity in prefrontal cortex correlates with the combined taste and healthiness outcome at stake during dietary self-control challenges in two independent datasets.

Discussion

We demonstrated an association between BOLD activity during the successful reappraisal of emotional stimuli and the level of dietary self-control shown in a separate food choice task. Specifically, greater increase in BOLD signals in a distributed set of cortical and subcortical regions during successful emotional reappraisal was associated with better dietary self-control. Notably, many of the regions that showed this cross-domain correlation were more active for successful relative to failed reappraisal trials within our current and in previous emotion regulation experiments (see Buhle et al. (2014) for review). Together these results are consistent with the idea that neural processes related to the reappraisal of emotional stimuli may also facilitate dietary self-control.

Despite the seemingly straightforward answer to one of the questions motivating our experiments, our findings also contain surprises that raised intriguing questions and prompted us to conduct further analyses. For example, the relationship between BOLD activity and regulation success across tasks was not symmetric. We didn’t find a significant relationship between BOLD activity during dietary self-control and self-reported reappraisal success. This may mean that stimulus reappraisal is one means of facilitating dietary self-control, but that the neural

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

processes mediating dietary self-control are not directly relevant to stimulus reappraisal.

However, there are several other plausible explanations for this asymmetric relationship. The lack of correlation between food choice BOLD activity and reappraisal success may also be due to individual differences in how the affective ratings are subjectively reported. Recall that we have only subjective self-reports of success in the emotion reappraisal task. Moreover, the interpretation of this null result is complicated by the fact that the fMRI results from the current food choice task differed from previous studies that used similar tasks. In contrast to them (Hare et al., 2009; Hare et al., 2011; Maier et al., 2015; Spetter et al., 2017; van Meer et al., 2017), we did not find significantly increased BOLD activity in the PFC as a function of dietary self-control success.

Despite not showing any significant increase in PFC as a function of self-control, the participants in the current sample often made the healthier choice when faced with dietary self-control challenges. In fact, the dietary self-control success rate in the current sample is among the highest we have observed across several similar experiments. Even so, the behavioral analysis showed that participants were tempted by highly palatable food items, more often failing to forego eating unhealthy items as they became more tasty. They were also sensitive to the "health cost" of unhealthy foods, being more likely to eat a tasty-unhealthy food if it was relatively less unhealthy (i.e. if the potential negative impact on health was low). These results indicate that participants remained sensitive to health and tastiness attributes and did not simply follow a rule. Instead, they suggest that participants tried to actively modulate their behavior based on taste and health considerations.

Why, then, does the self-control success BOLD contrast in our dataset differ from the results in previous studies? One potential reason is that, although participants made active goal-directed choices, they also showed a bias toward refusing to eat the food items in terms of both choice outcomes and response times (i.e. faster refuse responses). We presented participants with self-control challenges on approximately

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

75% of the trials. In challenge trials, participants most often faced decisions in which success required them to refuse palatable-unhealthy foods. A bias toward refusing would facilitate self-control in such cases. Indeed, the mean self-control success for refusing palatable-unhealthy foods was 77%. Furthermore, within this subset of challenges, successful self-control decisions were actually faster than choices to give into the taste temptations. The correlations between activity in visual processing regions and self-control in our data and previous EEG studies (Harris et al., 2013) also suggest that participants may strategically bias information processing or decision strategies early in, or even prior to, choices in order to facilitate self-control.

Unlike the palatable-unhealthy challenges, self-control success was low in unpalatable-healthy trials. The mean success rate for accepting unpalatable-healthy foods was only 19%. Successful choices were slower than failures in this type of challenge as well. This is the opposite response-time pattern to that seen in palatable-unhealthy challenges.

The difference in self-control success between challenge types is consistent with previous reports, but the pattern of response times differs (Hare et al., 2009; Demos et al., 2017). In previous studies, self-control response times were generally slower or not significantly different than decisions that did not present a self-control challenge. The Hare et al. (2009) study upon which the current food choice task was based did not tailor the choice set to each individual and the median percentage of self-control challenges was only 22%. In other words, challenges occurred relatively rarely in that study, but were common in our current implementation of the task.

Theories of self-control predict that the frequency of self-control challenges will influence the probability of engaging in regulation. The key assumption in these theories is that self-regulation entails some form of costly monitoring and effort that decision makers seek to minimize. Therefore, an individual will use self-control only when the cost of monitoring and trying to influence value computations (i.e. regulating) is smaller than the expected benefit of doing so (Botvinick and Rosen, 2009; Kool et al., 2010; McGuire and Botvinick, 2010; Kool et al., 2013; Shenhav et

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

al., 2013; Shenhav et al., 2017). This calculation depends on how important it is to the decision maker to choose healthy, and the state of the environment. For example, Brocas and Carillo (2014), theorize that in an environment consisting mainly of palatable-unhealthy items, an individual could minimize regulation costs by deciding *a priori* not consume foods unless she detects a healthy option rather than actively regulating on each trial. The pattern of reaction times in our data (faster refusals) is consistent with such a strategy. However, these theories also assume that individuals track what is at stake or the importance of each decision.

Therefore, we conducted an exploratory analysis to look for patterns of BOLD activity that correlated with the self-control stake size on each trial. We defined the stakes as the sum of what could be gained and lost in each self-control challenge (see Eq. 5). We found that BOLD activity in prefrontal cortex correlated with the stake size in the current participant sample, and that this result replicated when we repeated the same analysis in an independent dataset (Maier et al., 2015). These results suggest that individuals track what is at stake in each self-control challenge as the theories mentioned above predict.

In summary, we cautiously speculate that our task design permitted a simplifying strategy that allowed participants to make healthy choices with less need for choice-specific dlPFC-based regulation or modulation of the value computation process. Specifically, we think that the high frequency of self-control challenge trials together with the high proportion of palatable-unhealthy options within those trials prompted participants to bias their choices toward refusing to eat the proffered food items. This bias to refuse to eat food items may have reduced the need for trial-wise dlPFC engagement. This pattern of behavior may also reflect a shift from reactive to proactive forms of self-control during dietary choice (Braver, 2012; Duckworth et al., 2016). Therefore, we interpret our results from the food choice task as evidence for context-dependent adaptations in self-control strategies. This context-specificity has important implications for the design and utilization of food choice and other paradigms designed to probe self-control and neural activity. However, we emphasize that we can only speculate at this point and further

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

research examining the recruitment of dlPFC for self-control in different choice environments is needed to test these hypotheses more directly.

In contrast to the food choice task, our fMRI results for the emotional stimulus reappraisal task were quite consistent with previous reports on the regulation of responses to affective stimuli (Ochsner et al., 2002; Ochsner and Gross, 2005; Wager et al., 2008; Buhle et al., 2014; Kohn et al., 2014; Morawetz et al., 2017a) or food images (Hollmann et al., 2012; Han et al., 2018). Previous studies of emotion reappraisal have generally focused on the reappraisal of negative scenes and emotional reactions. Here, we extended the emotion reappraisal task to include the regulation of positive affective responses as well. Participants successfully regulated their reactions to both positive and negative stimuli. We did not find any significant differences in BOLD activity during positive versus negative emotion reappraisal. These results suggest that similar systems mediate the reappraisal of both affective valences. However, the standard cautions about (over-)interpreting null results apply to this result as well.

In conclusion, we found that BOLD activity during emotion reappraisal is positively correlated with dietary self-control. In the case of dietary self-control, we can think of modulating the subjective values placed on the tastiness and healthiness attributes as a modification of the valuation or appraisal process used to place an overall value on the food items. This re- or modified appraisal of the food items leads to healthier choices, which is the goal of dietary self-control. Our findings thus suggest that the neural systems supporting emotion reappraisal can generalize to other behavioral contexts that require reevaluation to conform to the current goal.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

References

Bagby RM, Parker JD, Taylor GJ (1994) The twenty-item Toronto Alexithymia Scale--I. Item selection and cross-validation of the factor structure. J Psychosom Res 38:23-32.

Bartra O, McGuire JT, Kable JW (2013) The valuation system: a coordinate-based meta-analysis of BOLD fMRI experiments examining neural correlates of subjective value. Neuroimage 76:412-427.

Baumeister S, Wolf I, Hohmann S, Holz N, Boecker-Schlier R, Banaschewski T, Brandeis D (2018) The impact of successful learning of self-regulation on reward processing in children with ADHD using fMRI. Atten Defic Hyperact Disord.

Beadman M, Das RK, Freeman TP, Scragg P, West R, Kamboj SK (2015) A comparison of emotion regulation strategies in response to craving cognitions: Effects on smoking behaviour, craving and affect in dependent smokers. Behav Res Ther 69:29-39.

Beck AT, Steer RA, Brown GK (1978) Beck depression inventory. New York: Psychological Corporation.

Bertsch K, Roelofs K, Roch PJ, Ma B, Hensel S, Herpertz SC, Volman I (2018) Neural correlates of emotional action control in anger-prone women with borderline personality disorder. J Psychiatry Neurosci 43:161-170.

Boswell RG, Sun W, Suzuki S, Kober H (2018) Training in cognitive strategies reduces eating and improves food choice. Proc Natl Acad Sci U S A.

Botvinick MM, Rosen ZB (2009) Anticipation of cognitive demand during decision-making. Psychol Res 73:835-842.

Brainard DH (1997) The Psychophysics Toolbox. Spat Vis 10:433-436.

Braver TS, Barch DM (2002) A theory of cognitive control, aging cognition, and neuromodulation. Neurosci Biobehav Rev 26:809-817.

Brocas I, Carillo JD (2014) Value computation and value modulation: a dual-process theory of self-control. In. Los Angeles, CA, USA: University of Southern California, Department of Economics.

Buhle JT, Silvers JA, Wager TD, Lopez R, Onyemekwu C, Kober H, Weber J, Ochsner KN (2014) Cognitive reappraisal of emotion: a meta-analysis of human neuroimaging studies. Cereb Cortex 24:2981-2990.

Bürkner P-C (2017) brms: An R Package for Bayesian Multilevel Models Using Stan. Journal of Statistical Software 80:1-28.

Carpenter B, Gelman A, Hoffman M, Lee D, Goodrich B, Betancourt M, Brubaker MA, Guo J, Li P, Riddell A (2016) Stan: A probabilistic programming language. Journal of Statistical Software 20:1-37.

Christakou A, Brammer M, Rubia K (2011) Maturation of limbic corticostriatal activation and connectivity associated with developmental changes in temporal discounting. Neuroimage 54:1344-1354.

Clithero JA, Rangel A (2013) Informatic parcellation of the network involved in the computation of subjective value. Social cognitive and affective neuroscience.

Collette F, Hogge M, Salmon E, Van der Linden M (2006) Exploration of the neural substrates of executive functioning by functional neuroimaging. Neuroscience 139:209-221.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Crockett MJ, Braams BR, Clark L, Tobler PN, Robbins TW, Kalenscher T (2013) Restricting temptations: neural mechanisms of precommitment. Neuron 79:391-401.

Decker JH, Figner B, Steinglass JE (2015) On Weight and Waiting: Delay Discounting in Anorexia Nervosa Pretreatment and Posttreatment. Biol Psychiatry 78:606-614.

Delgado MR, Nearing KI, Ledoux JE, Phelps EA (2008) Neural circuitry underlying the regulation of conditioned fear and its relation to extinction. Neuron 59:829-838.

Demos KE, McCaffery JM, Thomas JG, Mailloux KA, Hare TA, Wing RR (2017) Identifying the mechanisms through which behavioral weight-loss treatment improves food decision-making in obesity. Appetite 114:93-100.

Desikan RS, Ségonne F, Fischl B, Quinn BT, Dickerson BC, Blacker D, Buckner RL, Dale AM, Maguire RP, Hyman BT, Albert MS, Killiany RJ (2006) An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. Neuroimage 31:968-980.

Dosenbach NU, Fair DA, Miezin FM, Cohen AL, Wenger KK, Dosenbach RA, Fox MD, Snyder AZ, Vincent JL, Raichle ME, Schlaggar BL, Petersen SE (2007) Distinct brain networks for adaptive and stable task control in humans. Proc Natl Acad Sci U S A 104:11073-11078.

Drobetz R, Hanggi J, Maercker A, Kaufmann K, Jancke L, Forstmeier S (2014) Structural brain correlates of delay of gratification in the elderly. Behav Neurosci 128:134-145.

Duckworth AL, Kern ML (2011) A Meta-Analysis of the Convergent Validity of Self-Control Measures. J Res Pers 45:259-268.

Duckworth AL, Tsukayama E (2015) Domain-specificity in self-control. In: Character: New directions from philosophy, psychology, and theology (Miller C, Furr R, Knobel A, Fleeson W, eds), pp 393-411: Oxford University Press.

Duncan J (2010) The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour. Trends Cogn Sci 14:172-179.

Enax L, Hu Y, Trautner P, Weber B (2015) Nutrition labels influence value computation of food products in the ventromedial prefrontal cortex. Obesity (Silver Spring) 23:786-792.

Etkin A, Buchel C, Gross JJ (2015) The neural bases of emotion regulation. Nat Rev Neurosci 16:693-700.

Franz M, Popp K, Schaefer R, Sitte W, Schneider C, Hardt J, Decker O, Braehler E (2008) Alexithymia in the German general population. Soc Psychiatry Psychiatr Epidemiol 43:54-62.

Garland EL, Hanley AW, Bedford CE, Zubieta JK, Howard MO, Nakamura Y, Donaldson GW, Froeliger B (2018) Reappraisal deficits promote craving and emotional distress among chronic pain patients at risk for prescription opioid misuse. J Addict Dis:1-9.

Giuliani NR, Calcott RD, Berkman ET (2013) Piece of cake. Cognitive reappraisal of food craving. Appetite 64:56-61.

Giuliani NR, Mann T, Tomiyama AJ, Berkman ET (2014) Neural systems underlying the reappraisal of personally craved foods. J Cogn Neurosci 26:1390-1402.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Glover GH, Li TQ, Ress D (2000) Image-based method for retrospective correction of physiological motion effects in fMRI: RETROICOR. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine 44:162-167.

Gross JJ (1998) The Emerging Field of Emotion Regulation: An Integrative Review. Review of General Psychology 2:271-299.

Grühn D, Scheibe S (2008) Age-related differences in valence and arousal ratings of pictures from the International Affective Picture System (IAPS): Do ratings become more extreme with age? Behav Res Methods 40:512-521.

Han JE, Boachie N, Garcia-Garcia I, Michaud A, Dagher A (2018) Neural correlates of dietary self-control in healthy adults: A meta-analysis of functional brain imaging studies. Physiol Behav 192:98-108.

Hare TA, Camerer CF, Rangel A (2009) Self-control in decision-making involves modulation of the vmPFC valuation system. Science (New York, NY) 324:646-648.

Hare TA, Malmaud J, Rangel A (2011) Focusing attention on the health aspects of foods changes value signals in vmPFC and improves dietary choice. The Journal of neuroscience : the official journal of the Society for Neuroscience 31:11077-11087.

Harris A, Hare T, Rangel A (2013) Temporally dissociable mechanisms of self-control: early attentional filtering versus late value modulation. The Journal of neuroscience : the official journal of the Society for Neuroscience 33:18917-18931.

Harvey AK, Pattinson KTS, Brooks JCW, Mayhew SD, Jenkinson M, Wise RG (2008) Brainstem functional magnetic resonance imaging: disentangling signal from physiological noise. Journal of magnetic resonance imaging : JMRI 28:1337-1344.

Hautzinger M, Bailer M, Worall H, Keller F (1995) Beck-Depressions-Inventar. Bern: Verlag Hans Huber.

Heatherton TF, Wagner DD (2011) Cognitive neuroscience of self-regulation failure. Trends Cogn Sci 15:132-139.

Hill PF, Yi R, Spreng RN, Diana RA (2017) Neural congruence between intertemporal and interpersonal self-control: Evidence from delay and social discounting. Neuroimage 162:186-198.

Hollmann M, Hellrung L, Pleger B, Schlogl H, Kabisch S, Stumvoll M, Villringer A, Horstmann A (2012) Neural correlates of the volitional regulation of the desire for food. Int J Obes (Lond) 36:648-655.

Hutcherson CA, Plassmann H, Gross JJ, Rangel A (2012) Cognitive regulation during decision making shifts behavioral control between ventromedial and dorsolateral prefrontal value systems. J Neurosci 32:13543-13554.

Hutton C, Josephs O, Stadler J, Featherstone E, Reid A, Speck O, Bernarding J, Weiskopf N (2011) The impact of physiological noise correction on fMRI at 7 T. Neuroimage 57:101-112.

Jimura K, Chushak MS, Westbrook A, Braver TS (2018) Intertemporal Decision-Making Involves Prefrontal Control Mechanisms Associated with Working Memory. Cereb Cortex 28:1105-1116.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Kasper L, Bollmann S, Diaconescu AO, Hutton C, Heinzle J, Iglesias S, Hauser TU, Sebold M, Manjaly ZM, Pruessmann KP, Stephan KE (2017) The PhysIO Toolbox for Modeling Physiological Noise in fMRI Data. J Neurosci Methods 276:56-72.

Kober H, Mende-Siedlecki P, Kross EF, Weber J, Mischel W, Hart CL, Ochsner KN (2010) Prefrontal-striatal pathway underlies cognitive regulation of craving. Proc Natl Acad Sci U S A 107:14811-14816.

Kohn N, Eickhoff SB, Scheller M, Laird AR, Fox PT, Habel U (2014) Neural network of cognitive emotion regulation--an ALE meta-analysis and MACM analysis. Neuroimage 87:345-355.

Kool W, McGuire JT, Rosen ZB, Botvinick MM (2010) Decision making and the avoidance of cognitive demand. J Exp Psychol Gen 139:665-682.

Kool W, McGuire JT, Wang GJ, Botvinick MM (2013) Neural and behavioral evidence for an intrinsic cost of self-control. PloS one 8:e72626.

Kragel PA, Kano M, Van Oudenhove L, Ly HG, Dupont P, Rubio A, Delon-Martin C, Bonaz BL, Manuck SB, Gianaros PJ, Ceko M, Reynolds Losin EA, Woo CW, Nichols TE, Wager TD (2018) Generalizable representations of pain, cognitive control, and negative emotion in medial frontal cortex. Nat Neurosci 21:283-289.

Kross E, Mischel W (2010) From stimulus control to selfcontrol: Towards an integrative understanding of the processes underlying willpower.

Kross E, Ayduk O, Mischel W (2005) When asking “why” does not hurt distinguishing rumination from reflective processing of negative emotions. Psychological science 16:709-715.

Kruschke JK (2013) Bayesian estimation supersedes the t test. J Exp Psychol Gen 142:573-603.

Kruschke JK (2015) Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan, Second Edition: Academic Press / Elsevier.

Lang PJ, Bradley MM, Cuthbert BN (1999) International affective picture system (IAPS): Instruction manual and affective ratings. The center for research in psychophysiology, University of Florida.

Langner R, Leiberg S, Hoffstaedter F, Eickhoff SB (2018) Towards a human self-regulation system: Common and distinct neural signatures of emotional and behavioural control. Neurosci Biobehav Rev 90:400-410.

Lee SH, Im JJ, Oh JK, Choi EK, Yoon S, Bikson M, Song IU, Jeong H, Chung YA (2018) Transcranial direct current stimulation for online gamers: A prospective single-arm feasibility study. J Behav Addict:1-5.

Luerssen A, Gyurak A, Ayduk O, Wendelken C, Bunge SA (2015) Delay of gratification in childhood linked to cortical interactions with the nucleus accumbens. Soc Cogn Affect Neurosci 10:1769-1776.

Maier SU, Hare TA (2017) Higher Heart-Rate Variability Is Associated with Ventromedial Prefrontal Cortex Activity and Increased Resistance to Temptation in Dietary Self-Control Challenges. J Neurosci 37:446-455.

Maier SU, Makwana AB, Hare TA (2015) Acute Stress Impairs Self-Control in Goal-Directed Choice by Altering Multiple Functional Connections within the Brain's Decision Circuits. Neuron 87:621-631.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

McGuire JT, Botvinick MM (2010) Prefrontal cortex, cognitive control, and the registration of decision costs. Proc Natl Acad Sci U S A 107:7922-7926.

Mischel W, Moore B (1973) Effects of attention to symbolically presented rewards on self-control. J Pers Soc Psychol 28:172-179.

Mischel W, Underwood B (1974) Instrumental ideation in delay of gratification. Child Dev 45:1083-1088.

Mischel W, Baker N (1975) Cognitive Appraisals and Transformations in Delay Behavior. J Pers Soc Psychol 31:254-261.

Mischel W, Ebbesen EB, Zeiss AR (1972) Cognitive and attentional mechanisms in delay of gratification. J Pers Soc Psychol 21:204-218.

Morawetz C, Bode S, Derntl B, Heekeren HR (2017a) The effect of strategies, goals and stimulus material on the neural mechanisms of emotion regulation: A meta-analysis of fMRI studies. Neurosci Biobehav Rev 72:111-128.

Morawetz C, Bode S, Baudewig J, Heekeren HR (2017b) Effective amygdala-prefrontal connectivity predicts individual differences in successful emotion regulation. Soc Cogn Affect Neurosci 12:569-585.

Mumford JA, Poline JB, Poldrack RA (2015) Orthogonalization of regressors in FMRI models. PLoS One 10:e0126255.

Ochsner KN, Gross JJ (2005) The cognitive control of emotion. Trends Cogn Sci 9:242-249.

Ochsner KN, Silvers JA, Buhle JT (2012) Functional imaging studies of emotion regulation: a synthetic review and evolving model of the cognitive control of emotion. Ann N Y Acad Sci 1251:E1-24.

Ochsner KN, Bunge SA, Gross JJ, Gabrieli JD (2002) Rethinking feelings: an FMRI study of the cognitive regulation of emotion. J Cogn Neurosci 14:1215-1229.

Penny W, Friston K, Ashburner J, Kiebel S, Nichols TE (2006) Statistical Parametric Mapping: The Analysis of Functional Brain Images. London: Academic Press.

Plummer M (2003) JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. In: Proceedings of the 3rd international workshop on distributed statistical computing.

Pudel V, Westenhöfer S (1989) Fragebogen zum Ernährungsverhalten.

Reader SW, Lopez RB, Denny BT (2018) Cognitive reappraisal of low-calorie food predicts real-world craving and consumption of high- and low-calorie foods in daily life. Appetite 131:44-52.

Ridderinkhof KR, Ullsperger M, Crone EA, Nieuwenhuis S (2004) The role of the medial frontal cortex in cognitive control. Science 306:443-447.

Scherer KR, Schorr A, Johnstone T (2001) Appraisal processes in emotion: Theory, methods, research: Oxford University Press.

Schmidt L, Tusche A, Manoharan N, Hutcherson C, Hare T, Plassmann H (2018) Neuroanatomy of the vmPFC and dlPFC Predicts Individual Differences in Cognitive Regulation During Dietary Self-Control Across Regulation Strategies. J Neurosci 38:5799-5806.

Schonberg T, Bakkour A, Hover AM, Mumford JA, Poldrack RA (2014) Influencing food choices by training: evidence for modulation of frontoparietal control signals. J Cogn Neurosci 26:247-268.

Shahbabaie A, Ebrahimpoor M, Hariri A, Nitsche MA, Hatami J, Fatemizadeh E, Oghabian MA, Ekhtiari H (2018) Transcranial DC stimulation modifies

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

functional connectivity of large-scale brain networks in abstinent methamphetamine users. Brain Behav 8:e00922.

Sheffer CE, Bickel WK, Brandon TH, Franck CT, Deen D, Panissidi L, Abdali SA, Pittman JC, Lunden SE, Prashad N, Malhotra R, Mantovani A (2018) Preventing relapse to smoking with transcranial magnetic stimulation: Feasibility and potential efficacy. Drug Alcohol Depend 182:8-18.

Shenhav A, Botvinick MM, Cohen JD (2013) The expected value of control: an integrative theory of anterior cingulate cortex function. Neuron 79:217-240.

Shenhav A, Musslick S, Lieder F, Kool W, Griffiths TL, Cohen JD, Botvinick MM (2017) Toward a rational and mechanistic account of mental effort. Annu Rev Neurosci 40.

Siep N, Roefs A, Roebroeck A, Havermans R, Bonte M, Jansen A (2012) Fighting food temptations: the modulating effects of short-term cognitive reappraisal, suppression and up-regulation on mesocorticolimbic activity related to appetitive motivation. Neuroimage 60:213-220.

Silvers JA, Insel C, Powers A, Franz P, Weber J, Mischel W, Casey BJ, Ochsner KN (2014) Curbing craving: behavioral and brain evidence that children regulate craving when instructed to do so but have higher baseline craving than adults. Psychol Sci 25:1932-1942.

Spetter MS, Malekshahi R, Birbaumer N, Luhrs M, van der Veer AH, Scheffler K, Spuckti S, Preissl H, Veit R, Hallschmid M (2017) Volitional regulation of brain responses to food stimuli in overweight and obese subjects: A real-time fMRI feedback study. Appetite 112:188-195.

Svaldi J, Tuschen-Caffier B, Biehl SC, Gschwendtner K, Wolz I, Naumann E (2015) Effects of two cognitive regulation strategies on the processing of food cues in high restrained eaters. An event-related potential study. Appetite 92:269-277.

Szasz PL, Szentagotai A, Hofmann SG (2012) Effects of emotion regulation strategies on smoking craving, attentional bias, and task persistence. Behav Res Ther 50:333-340.

Tabibnia G, Monterosso JR, Baicy K, Aron AR, Poldrack RA, Chakrapani S, Lee B, London ED (2011) Different forms of self-control share a neurocognitive substrate. J Neurosci 31:4805-4810.

van Meer F, van der Laan LN, Viergever MA, Adan RAH, Smeets PAM, Consortium IF (2017) Considering healthiness promotes healthier choices but modulates medial prefrontal cortex differently in children compared with adults. Neuroimage 159:325-333.

Wager TD, Davidson ML, Hughes BL, Lindquist MA, Ochsner KN (2008) Prefrontal-subcortical pathways mediating successful emotion regulation. Neuron 59:1037-1050.

Webb TL, Miles E, Sheeran P (2012) Dealing with feeling: a meta-analysis of the effectiveness of strategies derived from the process model of emotion regulation. Psychol Bull 138:775-808.

Winkler AM, Ridgway GR, Webster MA, Smith SM, Nichols TE (2014) Permutation inference for the general linear model. Neuroimage 92:381-397.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Yokum S, Stice E (2013) Cognitive regulation of food craving: effects of three cognitive reappraisal strategies on neural response to palatable foods. Int J Obes (Lond) 37:1565-1570.

Zhao LY, Tian J, Wang W, Qin W, Shi J, Li Q, Yuan K, Dong MH, Yang WC, Wang YR, Sun LL, Lu L (2012) The role of dorsal anterior cingulate cortex in the regulation of craving by reappraisal in smokers. PLoS One 7:e43598.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

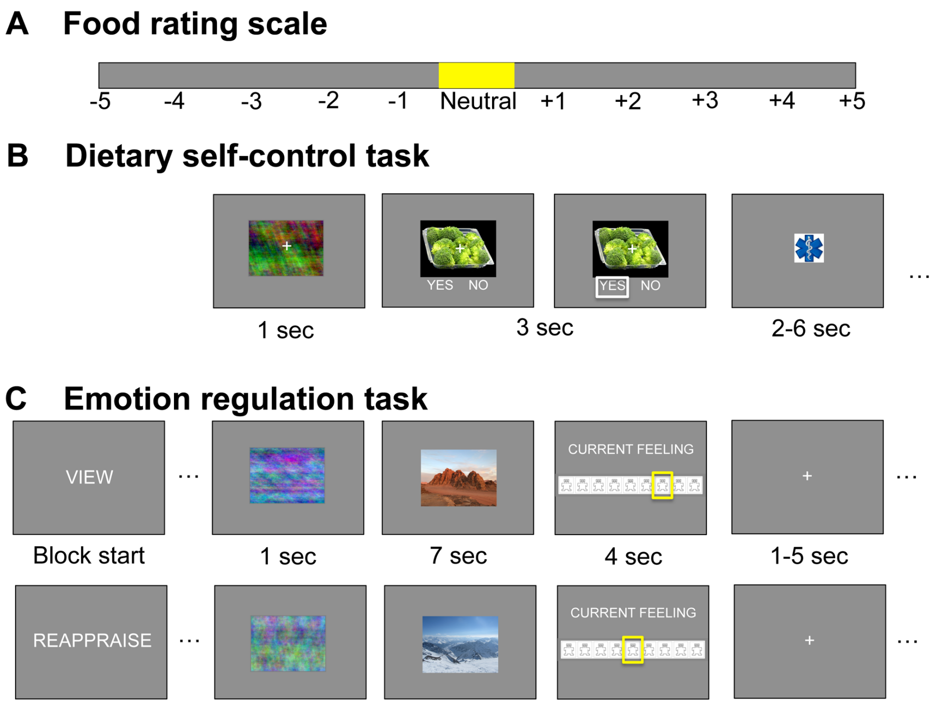

Figure 1. Behavioral tasks: Participants rated 180 food stimuli for taste and health using the rating scale depicted in panel **A**. Items rated "neutral" (falling within ± 5% of the scale around zero) were not presented in the choice set. The order of rating from -5 ("very untasty/unhealthy") to +5 ("very tasty/healthy") or vice versa was counterbalanced across participants.
In the dietary self-control task (**B**), participants had to choose what to eat at the end of the study. Stimuli were first presented for 1 second as a phase-scrambled image before participants had 3 seconds to choose whether to eat the food by pressing left or right (yes / no, order counterbalanced). The selected option was framed in white for 0.1 seconds. Trials were followed by a jittered 2-6 second inter trial interval.
In the emotion regulation task (**C**), participants were presented with positive, negative and neutral stimuli from the International Affective Picture System (IAPS). In blocks of 20 trials, participants were asked to "view" the positive and negative images or to "reappraise" the content such that the elicited feelings got weaker. Neutral images were only presented in the "view" condition. At the beginning of the block, a short verbal instruction for the block appeared for 1 second. An abbreviated reminder ("V" for "view" and "R" for "reappraise") was then displayed centered on the stimuli instead of the fixation cross. First a phase-scrambled version of the stimulus was presented for 1 second together with the cue. Then the image was revealed for 7 seconds, in which participants had to try and reappraise the content of the picture in order to regulate their feelings or let their feelings evolve naturally. Participants then had 4 seconds to rate their current feeling on a 9-point Self-Assessment-Manikin scale (4^{th} screen). Participants rated both foods and feelings using the same directionality (counterbalanced; from negative to positive or vice versa). Trials were separated by a jittered 1-5 second inter trial interval. After each block of reappraising or viewing, participants were given a 15-second break.
Note that in this figure, we have replaced the IAPS stimuli by our own photos for display purposes.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

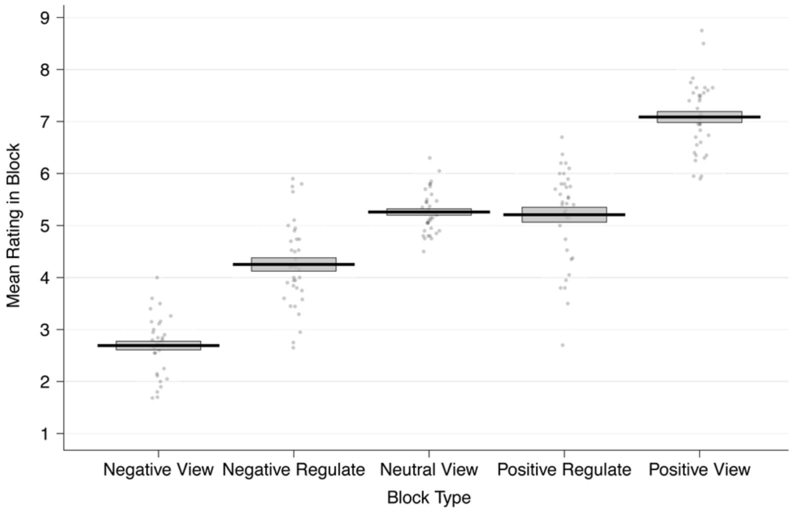

Figure 2. Emotion reappraisal behavior: Mean ratings made during the fMRI blocks by each participant. Ratings are aggregated over the negative view, negative regulate (reappraise), neutral view, positive regulate, and positive view blocks. Participants successfully reappraised negative images such that their emotions became more positive, and positive images such that their emotions became more negative. The black solid line represents the group mean and the gray box indicates the standard error of the mean. Each dot represents the mean ratings from one participant.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

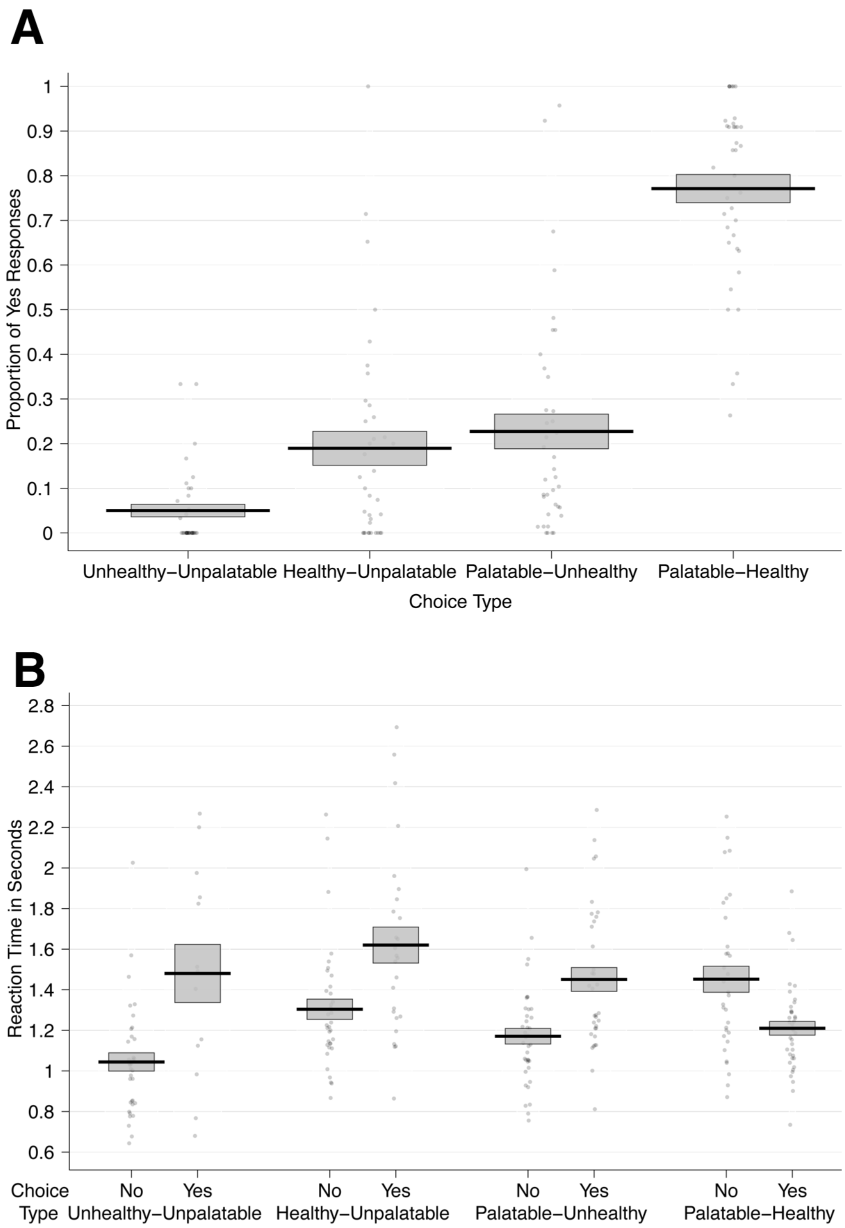

Figure 3. Dietary choice behavior: Panel **A** shows the proportion of "Yes" responses by choice category. Panel **B** shows the mean reaction times (RTs) over all participants for accepting and rejecting to eat foods from each of the four categories. In both panels, the black solid line represents the group mean and the gray box indicates the standard error of the mean. Each dot represents the proportion of "Yes" choices (A) or mean RT by choice (B) for one participant.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

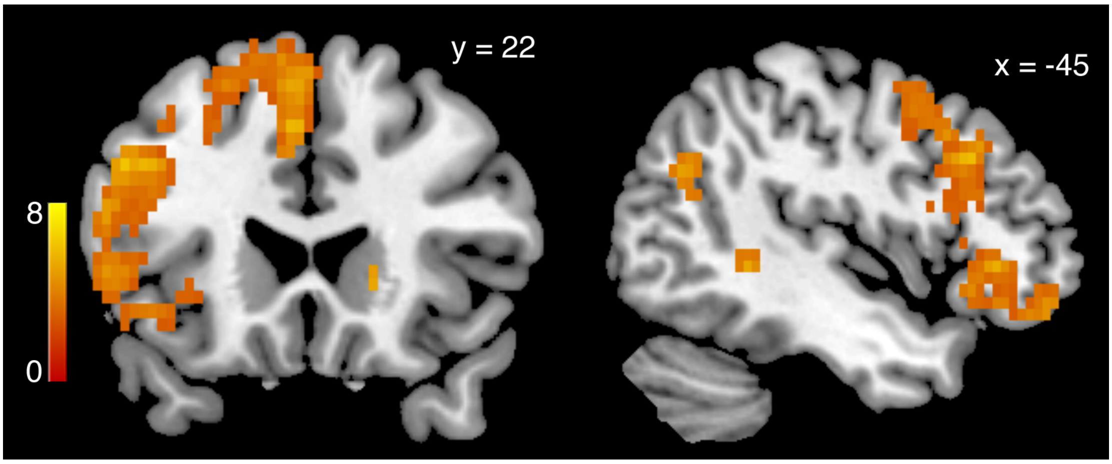

Figure 4. Successfully Reappraising > Viewing emotional content: Collapsed over both positive and negative stimuli, BOLD activity was greater in a widespread set of brain regions when successfully reappraising the content of emotional pictures in order to dampen the elicited emotions, compared to viewing the stimuli without altering the elicited feeling ($p < 0.05$, whole-brain corrected, derived from 5000 permutations of the data). The heat map represents T-statistics on a scale from 0 to 8 to keep the scale consistent across all subsequent figures.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

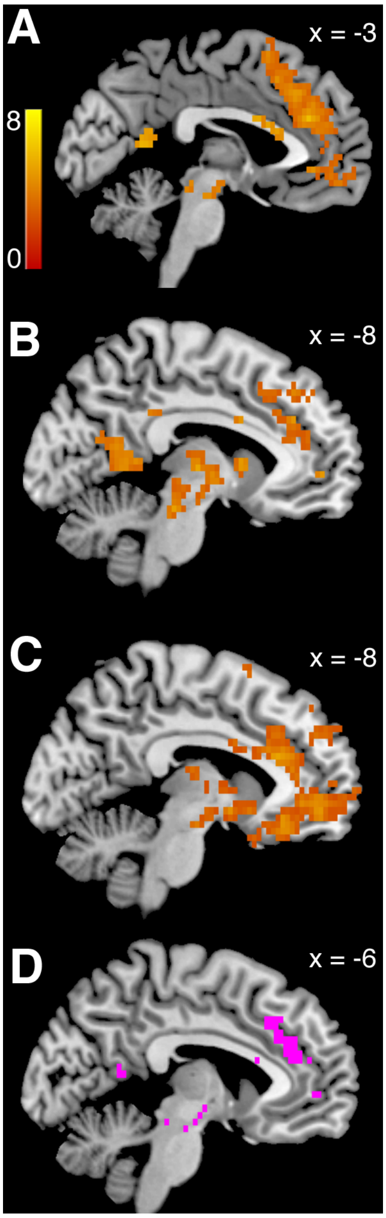

Figure 5. Neural activity at the time of food choice: **A)** BOLD activity increased with higher subjective food value in a set of regions associated with value-based choice. Panel **B)** depicts regions that increased their BOLD activity with higher health ratings, and panel **C)** regions that increased their activity with higher taste ratings of the presented foods. All results in panels A)-C) were significant at the threshold of $p < 0.05$, whole-brain corrected. The heat map represents T-statistics derived from 5000 permutations of the data. Panel **D)** depicts in pink the overlap of areas that significantly encoded subjective food value, as well as taste and health attributes separately. The conjunction threshold was $p < 0.05$, whole-brain corrected for family-wise error.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

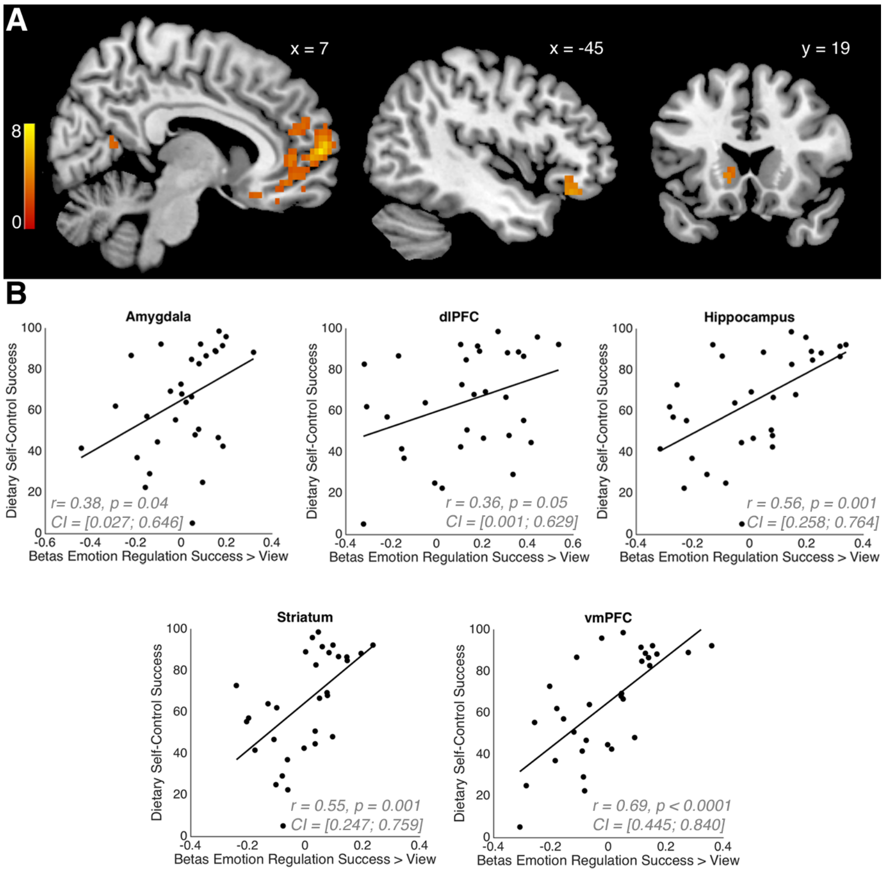

Figure 6. Emotion reappraisal and dietary self-control link: Panel **A)** shows results from a between-subjects regression relating individual differences in dietary self-control to voxel-wise differences in BOLD activity. Activation when successfully reappraising compared to viewing emotional content was higher in participants with better dietary self-control ($p < 0.025$, whole-brain corrected, T-statistics derived from 5000 permutations of the data). This suggests that participants whose neural activity changed more strongly during reappraisal of positive and negative stimuli were also the ones who were better at modulating their dietary decisions to refuse eating tasty-unhealthy foods or increase eating healthy-untasty foods. The scatter plots in panel **B)** illustrate the strength of this relationship. We performed region-of-interest (ROI) analyses in 5 regions that have previously been associated with reappraisal and decision-making in order to assess how strongly the BOLD activity change in Reappraisal > View conditions was related to dietary self-control success. The statistics in each plot give Pearson's rho (r) and its 95% Confidence Interval (CI) as well as the p-value (two-sided test) for the correlations between the mean BOLD activity for the contrast Reappraisal Success > View in each region and dietary self-control success (in percent).

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

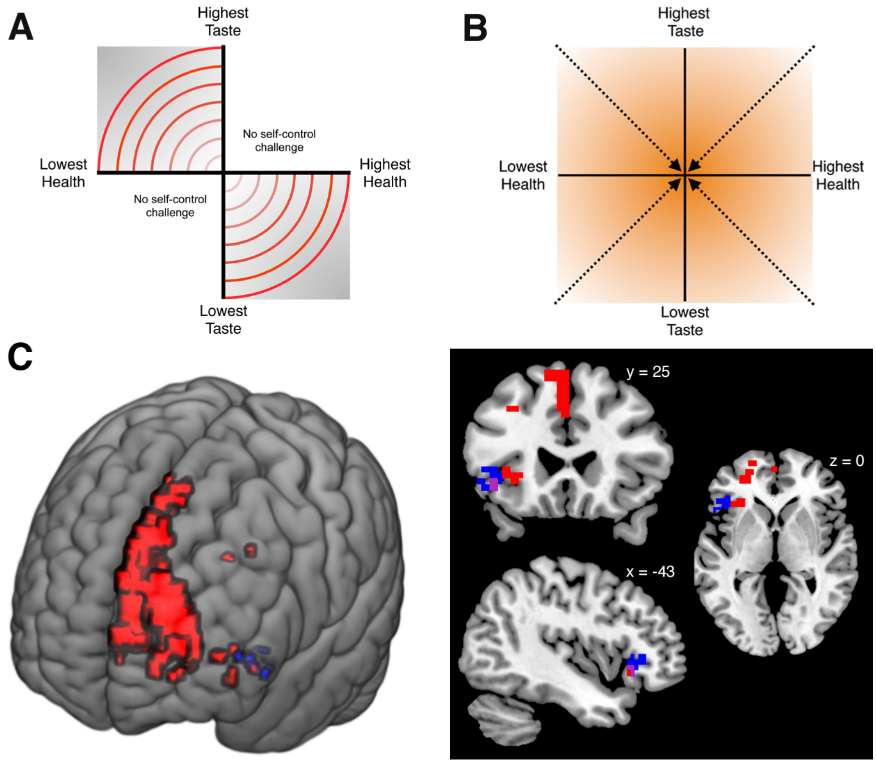

Figure 7. Self-control stakes: The sketch in panel **A)** explains the intuition for quantifying what is at stake in self-control. In the dietary self-control paradigm, any food can be categorized in one of four combinations of taste and health: tasty-healthy foods (upper right quadrant) and foods that are neither tasty nor healthy (lower left quadrant) present no challenge to self-control. When taste and health are not aligned, as foods become tastier and less healthy, the need for self-control increases (upper left quadrant). The same is true for the lower right quadrant as foods become healthier and a higher desire to eat tasty needs to be overcome. The intensifying red shade illustrates how both aspects become more important the farther from zero (the middle of the neutral zone of the rating scale) participants rated each aspect. Thus adding up the distance from zero for taste and health ($|tr| + |hr|$) determines the self-control stakes. Panel **B)** illustrates decision conflict or choice difficulty: Opposed to the stakes of self-control that increase with higher distance from zero, choices become more difficult when the food value approaches zero, which means the options of eating the food or nothing are very similar. Panel **C)** shows regions tracking the self-control stakes: BOLD activity in the lateral prefrontal cortex (PFC) increased with higher stakes or importance of self-control ($p < 0.05$, small-volume corrected within left lateral PFC, T-statistics derived from 5000 permutations of the data). The coloring shows a comparison between significant regions from the current sample (blue region) and a prior independent dataset in which we validated the stakes measure (Maier et al. 2015; red regions). In both datasets the need for self-control is tracked in the same brain region in the left inferior frontal gyrus (overlap indicated in purple in the inserts for the coronal and sagittal view).

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 1. Emotion ratings by condition.

A. Emotion ratings			
Condition	**Mean rating**	**Standard Deviation**	
Negative View	2.69	0.54	
Negative Regulate	4.25	0.81	
Neutral View	5.26	0.41	
Positive Regulate	5.21	0.90	
Positive View	7.09	0.67	
B. Regression results			
Fixed effects	**Beta estimate**	**Standard Deviation**	**95% Highest Density Interval**
(Intercept)	5.26	0.07	[5.13; 5.40]
Negative View	-2.57	0.10	[-2.77; -2.38]
Negative Regulate	-1.00	0.15	[-1.31; -0.70]
Positive Regulate	-0.06	0.17	[-0.39; 0.26]
Positive View	1.82	0.13	[1.57; 2.07]
Bayesian R^2	0.65	0.01	[0.64; 0.66]

A) Mean and standard deviation for the emotion ratings given in each block type.

B) Emotion ratings were modeled in a Bayesian linear regression model (specified in Eq. 1) as a function of block type, allowing participant-specific random intercepts and participant-specific random slopes. Block type was a factor with five levels (negative view, negative regulate, neutral view, positive regulate, positive view). The results show differences in the ratings with regard to neutral viewing as the baseline condition. The analyses in both A) and B) comprised N = 36 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 2. Basic food choice model.

Fixed effects	Beta estimate	Standard Deviation	95 % Highest Density Interval
(Intercept)	-1.02	0.39	[-1.81; -0.28]
Taste	**1.47**	**0.22**	**[1.04; 1.93]**
Health	**1.46**	**0.27**	**[0.95; 2.00]**
Task Order	-0.64	0.51	[-1.66; 0.34]
Male	-0.65	0.51	[-1.65; 0.36]
Hunger Level	0.05	0.23	[-0.40; 0.50]
Body Mass Index	0.35	0.24	[-0.11; 0.82]
Restrained Eating	0.09	0.25	[-0.41; 0.57]
Task Order X Taste	0.48	0.36	[-0.23; 1.19]
Task Order X Health	0.65	0.43	[-0.19; 1.53]
Bayesian R^2	**0.53**	**0.01**	**[0.51; 0.54]**

This table reports the results from the Bayesian logistic regression model specified in Equation 2 explaining food choices (i.e. eat/don't eat) by taste and health aspects. *Taste* and *Health* denoted standardized and mean-centered taste and health ratings for the current food. The model controlled for the following additional variables: *Task Order* was a factor controlling for the order in which the dietary choice and emotion reappraisal tasks were completed, which was counter balanced across participants. The model included the interaction of this factor with the taste and health decision attributes. *Male* was a factor accounting for self-reported gender. *Hunger Level* denoted the standardized and mean-centered hunger level that participants indicated before completing the food choice task. *Body Mass Index* was the standardized and mean-centered Body Mass Index. *Restrained Eating* denoted the standardized score on the restrained eating sub-scale of the Three Factor Eating Questionnaire. The regression included participant-specific intercepts and participant-specific random slopes for the Taste and Health ratings and their interaction with the factor Task Order. The coefficients (Beta estimates) listed are the means of the population level posterior distributions ± standard deviation (SD) and the 95% Highest Density Interval. The analysis comprised N = 38 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 3. Self-control success by taste and health attributes and challenge type.

Fixed effects	Beta estimate	Standard Deviation	95 % Highest Density Interval
(Intercept)	1.28	0.29	[0.73; 1.86]
Taste	**-1.40**	**0.33**	**[-2.04; -0.72]**
Health	**-2.75**	**0.44**	**[-3.67; -1.94]**
Type	**-1.89**	**0.91**	**[-3.77; -0.17]**
Type X Taste	**2.67**	**0.58**	**[1.63; 3.93]**
Type X Health	**2.69**	**0.71**	**[1.27; 4.09]**
Bayesian R^2	**0.62**	**0.01**	**[0.61; 0.63]**

This table reports the results from the Bayesian logistic regression model specified in Equation 3 explaining dietary self-control success (coded as a binary variable: 1 = success / 0 = no success) by taste and health aspects as well as challenge type. *Taste* and *Health* denoted between-participant standardized and mean-centered taste and health ratings for the current food. *Type* was a factor accounting for the type of challenge (levels: 0 = high-taste/low-health, 1 = high-health/low-taste). The model included the interaction of this factor with the taste and health decision attributes. The regression included participant-specific intercepts and participant-specific random slopes for the taste and health ratings and their interaction with the challenge type. The coefficients (Beta estimates) listed are the means of the population level posterior distributions ± standard deviation (SD) and the 95% Highest Density Interval. The analysis comprised N = 38 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 4. Reaction time model for food choices.

Fixed effects	Beta estimate	Standard Deviation	95% Highest Density Interval
(Intercept)	0.10	0.03	[0.05; 0.16]
Yes	**0.06**	**0.03**	**[0.01; 0.12]**
HTLH	-0.02	0.03	[-0.08; 0.03]
LTHH	**0.06**	**0.02**	**[0.02; 0.11]**
Yes X HTLH	**0.15**	**0.05**	**[0.05; 0.25]**
Yes X LTHH	**0.16**	**0.05**	**[0.07; 0.25]**
Bayesian R^2	**0.25**	**0.01**	**[0.22; 0.27]**

This table reports the results from the Bayesian regression model of reaction times for food choices specified in Equation 4. Reaction times were transformed using the natural logarithm. The variable *Yes* was coded with a value of 1 if participants chose to eat the depicted item and 0 otherwise. Trial type was coded as a factor with 3 categories (non-challenging trials as the reference category, and high-taste/low-health (*HTLH*) trials and low-taste/high-health (*LTHH*) trials as indicator variables). The regression included participant-specific intercepts and participant-specific random slopes for all regressors and interaction terms. The coefficients (Beta estimates) listed are the means of the population level posterior distributions ± standard deviation (SD) and the 95% Highest Density Interval. The analysis comprised N = 38 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 5. Reappraisal Success > View.

Region	*Side*	*MNI Coordinates*	*TFCE t-stat*
Supplementary Motor Cortex	L	-5 9 61	7.21
Middle Temporal Gyrus.	L	-50 -44 0	8.01
Lateral Occipital Cortex, superior div.	L	-50 -64 25	6.03
Middle Temporal Gyrus	L	-58 -14 -18	5.96
Caudate	R	15 19 7	6.41
Temporal Pole	L	-52 9 -25	5.19
Caudate	L	-15 17 -4	5.31
Angular Gyrus	L	-48 -56 47	3.95

The contrast Reappraisal Success > View was collapsed across both positive and negative valence in order to test for domain-general regulation mechanisms. All reported regions were significant at $p < .05$ after whole brain family-wise error correction. Threshold free cluster enhancement (TFCE) test statistics and their null distribution (5000 permutations) were calculated with the Randomise package in FSL. Sub-peaks within clusters formed by contiguous voxels are reported when separated by a distance of 20mm. Anatomical labels were derived from the Harvard-Oxford cortical and subcortical atlases. The analysis comprised N = 35 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 6. Subjective food value representations.

Region	*Side*	*MNI Coordinates*	*TFCE t-stat*
Paracingulate Gyrus	L	-3 37 25	5.99
Brain Stem	R	10 -26 -14	5.79
Anterior Cingulate Gyrus	R	0 14 22	5.43
Precuneus	L	-3 -56 11	5.59
Orbital Frontal Cortex	L	-28 32 -14	4.36
Insular Cortex / Orbital Frontal Cortex	L	-30 9 -14	5.09
White Matter	R	10 17 22	4.36
Medial Frontal Cortex	L	-10 34 -18	4.65
Orbital Frontal Cortex	L	-25 24 -22	4.48
Amygdala	R	13 -6 -11	5.31

All reported regions were significant at $p < .05$ after whole brain family-wise error correction. Threshold free cluster enhancement (TFCE) test statistics and their null distribution (5000 permutations) were calculated with the Randomise package in FSL. Sub-peaks within clusters formed by contiguous voxels are reported when separated by a distance of 20mm. Anatomical labels were derived from the Harvard-Oxford cortical and subcortical atlases. The analysis comprised N = 37 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 7. Health value representations.

Region	*Side*	*MNI Coordinates*	*TFCE t-stat*
Superior Frontal Gyrus	L	-13 37 47	6.26
Frontal Pole	L	-45 42 14	5.63
Caudate	L	-10 9 7	5.32
Precuneus	L	-3 -56 11	6.13
Posterior Cingulate Gyrus	L	-5 -36 32	5.45
Caudate	R	13 9 11	5.73
Anterior Cingulate Gyrus	L	-3 7 25	5.28
White Matter	R	10 17 22	5.66
Anterior Cingulate Gyrus	L	-3 22 18	4.25
Superior Lateral Occipital Cortex	L	-35 -66 47	5.7
Paracingulate Gyrus	L	-8 52 0	4.77
Anterior Cingulate Gyrus	L	-3 14 22	4.22

All reported regions were significant at $p < .05$ after whole brain family-wise error correction. Threshold free cluster enhancement (TFCE) test statistics and their null distribution (5000 permutations) were calculated with the Randomise package in FSL. Sub-peaks within clusters formed by contiguous voxels are reported when separated by a distance of 20mm. Anatomical labels were derived from the Harvard-Oxford cortical and subcortical atlases. The analysis comprised N = 37 participants.

Table 8. Taste value representations.

Region	*Side*	*MNI Coordinates*	*TFCE t-stat*
Orbital Frontal Cortex	R	25 24 -18	6.02
Frontal Pole	R	18 47 36	4.39
Supplementary Motor Cortex	L	-3 7 65	4.13
Posterior Cingulate Gyrus / Precuneus	L	-3 -51 14	4.7
Anterior Parahippocampal Gyrus	R	20 -19 -29	4.03
Superior Frontal Gyrus	L	-15 27 54	3.9

All reported regions were significant at $p < .05$ after whole brain family-wise error correction. Threshold free cluster enhancement (TFCE) test statistics and their null distribution (5000 permutations) were calculated with the Randomise package in FSL. Sub-peaks within clusters formed by contiguous voxels are reported when separated by a distance of 20mm. Anatomical labels were derived from the Harvard-Oxford cortical and subcortical atlases. The analysis comprised N = 37 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 9. Reappraisal Success > View correlates with dietary self-control success.

Region	*Side*	*MNI Coordinates*	*TFCE t-stat*
Frontal Pole	R	8 62 7	7.33
Precuneus	L	-3 -56 7	4.25
Temporal Occipital Fusiform Cortex	R	43 -61 -25	4.35
Cerebellum	L	-20 -86 -32	4.91
Caudate	L	-13 19 0	4.14
Posterior Parahippocampal Gyrus	L	-18 -26 -11	4.48
Orbital Frontal Cortex	L	-45 32 -14	4.96
Posterior Cingulate Gyrus	L	-3 -34 7	4.03
Lingual Gyrus / Occipital Pole	L	-3 -91 -18	4.05
Frontal Pole	L	-25 42 7	3.73
Cerebellum	R	28 -84 -32	4.74
Lingual Gyrus	R	15 -64 -11	5.1
Posterior Parahippocampal Gyrus	R	23 -34 -18	3.86
Temporal (Occipital) Fusiform Cortex	R	33 -39 -25	3.7
Cerebellum	R	3 -89 -29	3.68
Precuneus	R	13 -56 14	3.3
Corpus Callosum	L	-5 27 7	3.48
Planum Polare	L	-43 2 -18	5.04
Cerebellum	R	30 -59 -25	3.13
Cerebellum	R	35 -59 -58	4.37

All reported regions were significant at $p < .025$ after whole brain family-wise error correction. We Bonferroni-corrected for multiple comparisons because two separate analyses were required to obtain this result (assessment of dietary self-control success, and assessment of neural reappraisal correlates). Threshold free cluster enhancement (TFCE) test statistics and their null distribution (5000 permutations) were calculated with the Randomise package in FSL. Sub-peaks within clusters formed by contiguous voxels are reported when separated by a distance of 20mm. Anatomical labels were derived from the Harvard-Oxford cortical and subcortical atlases. The analysis comprised N = 31 participants.

bioRxiv preprint doi: https://doi.org/10.1101/542712; this version posted February 7, 2019. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC 4.0 International license.

Table 10. Regions tracking self-control stakes during self-control challenges in the dataset from Maier et al. (2015).

Region	*Side*	*MNI Coordinates*	*TFCE t-stat*
A. Small-volume corrected in left lateral PFC			
Superior Frontal Gyrus / Paracingulate Gyrus	L	-2 38 40	5.43
Orbital Frontal Cortex	L	-30 28 -4	4.48
Middle Frontal Gyrus	L	-32 23 40	4.5
Middle Frontal Gyrus	L	-40 16 43	4.14
Orbital Frontal Cortex	L	-40 31 -10	4.1
Frontal Operculum	L	-37 26 3	3.77
Orbital Frontal Cortex	L	-45 23 -7	4.3
B. Whole-brain corrected			
Paracingulate Gyrus	R	6 36 37	6.38
Precuneus	R	13 -65 34	5.35
Middle Frontal Gyrus	R	41 18 46	4.29
Middle Frontal Gyrus	R	36 26 46	5.05
Superior Lateral Occipital Cortex	R	53 -60 43	5.31
Frontal Operculum	R	43 23 -4	4.39
Angular Gyrus	R	51 -55 34	4.96
Insula	L	-30 21 -7	5.01

A) All reported regions were significant at $p < .05$ after small-volume correction for family-wise error in an anatomical mask of the left lateral prefrontal cortex. Threshold free cluster enhancement (TFCE) test statistics and their null distribution (5000 permutations) were calculated with the Randomise package in FSL. Sub-peaks within clusters formed by contiguous voxels are reported when separated by a distance of 20mm. Anatomical labels were derived from the Harvard-Oxford cortical and subcortical atlases.

B) All reported regions were significant at $p < .05$ after whole-brain correction for family-wise error. Threshold free cluster enhancement (TFCE) test statistics and their null distribution (5000 permutations) were calculated with the Randomise package in FSL. Sub-peaks within clusters formed by contiguous voxels are reported when separated by a distance of 20mm. Anatomical labels were derived from the Harvard-Oxford cortical and subcortical atlases.
The analyses in both A) and B) comprised all 51 participants of the study.