**Recruitment of dlPFC during dietary self-regulation predicts the transience of regulatory effects**

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**Abstract**

Recent work on the cognitive regulation of dietary decision making suggests that regulation can alter both the choices that people make in the moment, as well as longer-lasting preferences (Boswell, Sun, Suzuki, & Kober, 2018). However, it is unclear what mechanisms lead to temporary or more lasting change. To address this question, we used fMRI during a task employing cognitive regulation of food choice and assessed changes in food preference from baseline to post-regulation. We found evidence that regulation may result in a temporary reconfiguration of the neural drivers of choice, emphasizing goal-consistent value-related computations in the dorsolateral prefrontal cortex (dlPFC) and de-emphasizing goal-inconsistent value-related computations in the ventromedial prefrontal cortex. Moreover, we find that the extent to which the dlPFC was recruited to represent different regulatory goals during the moment of choice *negatively* predicted the extent to which those regulatory goals produced persistant changes in preference. Our results suggest that recruitment of the dlPFC in the service of regulation may have a downside: it is effective at changing behavior in the moment, but its effects on preferences are transient.

Keywords: Decision-making; dietary choice; cognitive regulation; ventromedial prefrontal cortex; dorsolateral prefrontal cortex**Introduction**

One of the perennial laments of dieters the world over centers around the difficulty of maintaining healthy eating practices. All too often, we set a goal to eat healthier or to simply eat less, and succeed for a few days or weeks only to have our core love of sugars and fats rear up at an inopportune moment. Recent research has pointed to the potential utility of value-based cognitive self-regulation—the use of memory, attention and executive control to alter the value we place on food—as a potential solution to this problem (Hare, Malmaud, & Rangel, 2011). This work suggests not only that cognitive self-regulation can be used to change the momentary values assigned to different foods, but also that regulatory effects can persist beyond the moment of active regulatory focus, leading to lasting changes in preference. More remarkably, these changes appear not to require active regulatory effort to maintain (Boswell et al., 2018; see also Denny et al., 2015 for a similar conclusion in the domain of emotion regulation). But this finding raises something of a puzzle: if self-regulatory efforts can alter not only momentary but also lasting preferences, why don’t more people learn to “dislike” cookies and ice cream? What determines whether self-regulatory efforts produce only transient rather than persistant changes in behavior? Here, we suggest that the answer may lie partly in the extent to which distinct neural mechanisms are recruited to accomplish a self-regulatory goal.

Prior research on the neural implementation of cognitive self-regulation in the domain of dietary choice consistently implicates the ventromedial prefrontal cortex (vmPFC) and the dorsolateral prefrontal cortex (dlPFC), although the literature paints a mixed picture regarding the precise role played by each of these regions. Some research suggests that cognitive regulation recruits the dlPFC—an area associated with cognitive control more generally, e.g., (Brass, Derrfuss, Forstmann, & von Cramon, 2005)—to alter computations in the ventromedial prefrontal cortex, a region consistently shown to correlate with decision values at the time of choice (Bartra, McGuire, & Kable, 2013; Clithero & Rangel, 2013). For example, regulation of craving appears to activate portions of the dlPFC and *reduce* activation in the vmPFC (Kober et al., 2010). Similarly, attempts to consider the healthiness of a food seem to activate the dlPFC, which appears, through functional connectivity, to modulate vmPFC representations of healthiness (Hare et al., 2011). Nevertheless, other research suggests that signals in the vmPFC might sometimes *resist* alteration by cognitive self-regulation. In these cases, neural patterns of response suggest that the dlPFC might represent a distinct value signal that shows more flexible, goal-consistent effects of regulation. For example, research suggests that attempts to decrease craving sometimes fail to alter vmPFC values signals (Hutcherson, Plassmann, Gross, & Rangel, 2012; Yokum & Stice, 2013). At the same time, the dlFPC shows reduced activation overall (consistent with the goal to reduce craving) as well as an increased association with explicitly expressed preference (Hutcherson et al, 2012). Other work using multivariate decoding analyses suggests a similar idea. When participants focused on healthy eating, vmPFC value signals showed little change as a function of regulatory condition, while dlPFC signals decoded healthiness more strongly and tastiness less strongly. When participants focused on considerations of tastiness, the opposite was observed (Tusche & Hutcherson, 2018).

It is currently unclear what might account for these discrepant findings. One possibility is that they reflect individual heterogeneity in the strategies or mechanisms used to accomplish regulatory goals. For example, some individuals might first attempt to alter their preferences through processes that target value signals in the vmPFC. If they succeed, no further effort is required. However, in cases where initial attempts to regulate fail to change vmPFC responding, individuals might resort to more effortful processes involving modulation of signals within the dlPFC. To the extent that such efforts are successful, it might be the dlPFC, rather than vmPFC, that ultimately guides the behavioral response. In this view, regulation might target both the vmPFC and the dlPFC, and both areas might be related to regulatory success, depending on the circumstances. Such a view is consistent with evidence that gray matter in *both* the vmPFC and the dlPFC positively predicts individual differences in regulatory success, across multiple forms of self-control tasks (Schmidt et al., 2018). This view is also consistent with recent research that suggests that both the dlPFC and vmPFC are independently predictive of choice in a sample of dieters focused on losing weight (Cosme, Ludwig, & Berkman, 2019).

How might such processes relate to the persistence or transience of self-regulatory efforts? We speculated that computations in the dlPFC might represent a mechanism for temporarily shifting attention towards momentarily goal relevant outcomes. Such a view is consistent with research suggesting that the dlPFC activates when contexts require a shift in attention towards new stimulus dimensions (Leong et al., 2017; Rudorf & Hare, 2014), as well as evidence that it represents attribute values in a goal-sensitive manner (Tusche & Hutcherson, 2018). While this mechanism might contribute to regulatory success in the moment, such effects are unlikely to last much beyond the moment of active regulatory focus, since they operate via an additional, effortful route to behavioral control. In contrast, we hypothesized that successful modulation of value signals in the vmPFC, which has a rich set of interconnections with regions involved in reward learning (e.g., amygdala and ventral striatum: Carmichael & Price, 1995; Haber, Kim, Mailly, & Calzavara, 2006), might produce more persistent shifts in preference towards regulatory goals.

Unfortunately, little is known regarding neural predictors of alterations in preference that persist beyond the moment of active regulation. Related work in the domain of emotion regulation suggests that it can produce lasting reductions in amygdala response (Denny et al., 2015) and that this effect might be driven by activity in the dlPFC during the moment of active regulatory focus (Erk et al., 2010). However, no study to date has examined the neural predictors of persistent regulatory effects of cognitive self-regulation on food choice.

We thus aimed to test several related hypotheses about the processes supporting both momentary and persistent dietary change as a result of cognitive self-regulation of value. Focusing on regions of the vmPFC and dlPFC showing evidence of value representations at the time of choice, we first asked whether instructed self-regulation of value produced goal-consistent changes in response in either or both of these regions. To do this, we first focused on two prominent regulatory strategies in the literature that emphasize different goals. In one, participants are asked to focus on a goal to decrease cravings and value for all foods encountered (Hutcherson et al., 2012). In the other, participants are asked to focus on a goal that more specifically emphasizes health considerations (i.e., a goal that decreases the value of unhealthy foods but increases the value of healthy foods: Bhanji & Beer, 2012; Hare et al., 2011; Harris, Hare, & Rangel, 2013; Tusche & Hutcherson, 2018) Bhanji et al., 2012; Tusche & Hutcherson, 2018). This allowed us to test for goal-specific effects of self-regulation on value-based responses in the vmPFC and dlPFC. Second, using a recently-developed analytical approach for identifying the unique and independent contribution of different brain regions to behavior (Cosme et al., 2019), we sought to determine whether regulation alters the independent influences of vmPFC and dlPFC on choice behavior. We speculated that this route might act as a compensatory mechanism that recruits the dlPFC in cases where self-regulation fails to alter signals in the vmPFC. Third, we assessed regulation-induced changes in liking of foods from baseline to post-regulation, asking whether individual differences in the neural responses of vmPFC and dlPFC during the moment of active regulatory focus predicted either persistent or momentary effects of regulation.

**Methods**

## **Participants**

Sixty-four healthy, right-handed individuals with normal or corrected-to-normal vision (forty-one females; mean age, 23.2; range, 18– 38) were recruited from the University of Toronto and surrounding community via postering and Facebook groups. Fourteen of these subjects were excluded from analysis: three withdrew before completing the experiment, and 11 had excessive head motion during scanning (see MRI data preprocessing section for exclusion criteria), leaving a total of 50 subjects (thirty-four females; mean age, 23.1; range, 18– 38; 1 African Canadian/Black, 25 Asian/Asian Canadian, 1 Asian/Asian Canadian, Southeast Asian/Indian, 3 Hispanic/Latino, 1 Southeast Asian/Chinese, 6 Southeast Asian/Indian, 1 Turkish, 1 West Indian, 10 White/Caucasian). Sample size was selected based on previous successful implementations of the task ([Hare et al., 2011a](https://elifesciences.org/articles/31185#bib22), Tusche & Hutcherson, 2018), and was also the largest N we could run that was consistent with our budget. Subjects were eligible only if they reported frequent consumption of the types of foods used in the study and had no history of psychiatric or neurological conditions. Subjects were paid $60 for participation with an additional $5 payment for punctuality and a $5 incentive paid to subjects who showed low motion during scanning. All participants gave informed consent and the University of Toronto Research Ethics Board approved all procedures.

**Tasks**

*Overview*

Prior to beginning the study, participants fasted for 3 hours, in order to motivate them to eat foods in the study. In order to assess whether and how neural activation during cognitive regulation of food value relates to changes in food liking, participants rated a set of 270 images of foods (described below in the Stimuli section) for momentary liking, rating them once before entering the scanner, and again after completing all scanner tasks. We defined “liking” for subjects as how much they would like to eat the presented food, in the amount shown on screen, “right now”, regardless of other considerations.

the food images presented to subjects in-scanner during the cognitive regulation taskfood stimulirated for liking pre-scanAlso note that we referred to subject choice during the scanner cognitive regulation task as “preference”, in order to differentiate it from the pre and post-scan “liking” ratings. Both terms, preference and liking, as we use them, fall under the larger umbrella of “wanting”, referring to the subject’s motivation to consume the food item (Pool et al., 2016).

After scanning, along with a repetition of the food stimuli liking ratings, participants also completed an attribute rating task, in which they made ratings of the subjectively perceived tastiness and healthiness of each food. Following completion of the attribute ratings, a single trial from the cognitive regulation task was drawn and the participant’s choice on that trial was implemented. Finally, participants completed a set of individual differences measures, were debriefed and paid. See figure XX for a visualization of the experimental structure.

*Stimuli*

Stimuli consisted of 135 different foods, designed to cover the full range of healthiness and tastiness (e.g., candy, chips, fruits, vegetables, etc.). Each food was displayed in one of two different quantities (e.g., a small amount of chips, a large amount of chips), presented on a plate or in a container set against a black background (see Figure 1 for an example). This yielded a total of 270 unique food images for use in the tasks described below.

*Cognitive Regulation Task*

On each trial of the cognitive regulation task, participants were presented with a food image for 4 seconds, during which time they had to indicate whether they would like to eat the food using a 4-point scale ranging from Strong No to Strong Yes (Figure 1). Importantly, decisions were made in one of three instructed conditions: focus on healthiness (HEALTH condition), focus on decreasing all craving (DECREASE condition), and focus on responding naturally (NATURAL condition). On HEALTH trials subjects were instructed to think about the nutritional and health benefits of the food while making their choice. On DECREASE trials subjects were told to avoid any craving or emotional response to the food while choosing. On NATURAL trials subjects were told to allow whatever thoughts and feelings arose while considering the food, and to choose based on those feelings. Subjects were instructed to respond honestly regardless of the instruction, and were motivated to do so, since they were hungry. They knew that one trial would be chosen randomly at the end of the experiment and that they would either receive the trial item (if they had responded “Weak Yes” or “Strong Yes”), or receive nothing (if they had responded “Weak No” or “Strong No”).

Task blocks began with the presentation of the regulatory instructions (i.e., one of the three regulatory conditions), reminding them of the mindset to adopt, followed by 10 consecutive trials where subjects were presented food stimuli, and indicated their desire to eat the food. Each scanning run consisted of one block of each instruction (i.e. condition), yielding 30 trials per run. Subjects completed nine runs for a total of 270 trials. In the first run subjects always began with a block of NATURAL trials. In the remaining runs the order of the three blocks was randomized.

Importantly, both food quantities of a specific food appeared in the same condition. Thus, each condition consisted of 45 specific foods presented in two quantities. This also meant that each food was only present in a single regulatory condition. The association of specific foods with specific goal conditions allowed us to examine how regulation might alter responses to foods, both generally, across all foods, as well as specifically, as a function of the food appearing in a particular condition. Foods were assigned to each condition for each subject such that baseline liking ratings were matched across conditions (see Liking Rating Task section below).

*Executive Control Tasks*

To localize brain areas associated with specific aspects of executive function, subjects also completed two localizer tasks in the scanner following the food choice trials. The first was a go/no-go (GNG) task, to test subjects’ ability to resist a prepotent response. The second was an attentional switching task [(Rogers and Monsell 1995)](https://paperpile.com/c/QR5P5l/vaIn). Because these tasks are not the focus of this investigation, we do not describe them further here.

*Liking Rating Task*

In order to measure changes in liking as a function of cognitive regulation, participants completed two rounds of a liking rating task, once before and once after the in-scanner cognitive regulation task. During this task subjects were shown 270 unique food images, as described in the Stimuli section, above. These were the same food images that subjects would be shown during the in-scanner cognitive regulation task. Subjects were instructed to indicate how much they would like to eat that food in the amount shown on screen. Subjects completed the task at their own pace, using a six-point Likert scale (1, “Strongly Dislike”; 6, “Strongly Like”). As a reminder, we defined “liking” for subjects as how much they would like to eat the presented food, in the amount shown on screen, “right now”, regardless of other considerations. We specified “right now” in an effort to prevent participants from attempting to make their responses consistent across the two rounds of ratings.

## *Attribute Ratings Task*

## Following completion of the post-scan Liking Rating Task, participants viewed all foods again (270 images of the 135 foods in two different serving sizes), and were asked to rate each food for subjectively perceived tastiness and healthiness, without taking into account other considerations. Ratings were made on a Likert Scale from 1 (Very untasty/unhealthy) to 6 (Very tasty/healthy). All foods were rated for one attribute, and then presented a second time and rated for the other attribute. The order in which participants rated the two attributes was randomized.

## **Analysis**

## *Behavioral Analyses*

Statistical analyses were conducted in R 3.6.1 (R Core Team, 2019, <https://www.R-project.org>). To examine how choice behavior differed during cognitive regulation, we computed a regression for each subject and each condition separately with the following fixed effects:

|  |  |
| --- | --- |
|  | (1) |

To compare across conditions, and to correlate individual differences with neural activation, we performed statistical analyses using the subject-level intercept () and slope () parameters for each variable for each condition.

Making inferences about how liking for foods changes following regulatory effort represents more of a challenge, in the sense that foods rated at the negative and positive ends of the scale (i.e., Strong Dislike, Strong Like) are constrained in their direction of movement (i.e., floor and ceiling effects). Thus, pre-task liking may partially determine the degree of change in post-task liking. To account for this issue, we characterized effects of regulation on change in post-task liking compared to baseline () using the following regression, computed separately for each subject and condition:

|  |  |
| --- | --- |
|  | (2) |

Examining the raw magnitude of these subject-level coefficients for a given condition permit us to make inferences about how the determinants of food-liking change from baseline. For example, if after controlling for pre-task liking, healthiness predicts a change in liking, then the coefficient on Healthiness should be positive. Similarly, if after controlling for pre-task liking, the intercept is negative, this suggests a general decrease in liking for foods in a specific condition. Comparing the magnitudes of these regression coefficients across conditions allows us to determine whether different forms of regulation result in distinct persistent changes in liking, beyond the moment of active regulatory focus. Coefficients for the subject-level terms also allow us to examine individual differences, and to link them to changes in neural activity during the regulation task.

## *MRI data acquisition*

Functional imaging was conducted using a Siemens Prisma 3.0 T MRI scanner, with a gradient strength of 80 mT/m and slew rate of 200 T/m/s. Gradient echo T2\*-weighted echoplanar images (EPI) were collected using a 32-channel head coil. To optimize functional sensitivity in the ventromedial prefrontal cortex (vmPFC), a key region of interest, we used a tilted acquisition in an oblique orientation of 30° to the anterior commissure–posterior commissure line. Each volume comprised 69 axial slices. A total of 1188 volumes were collected over nine scanning runs (132 volumes/run) during the experiment in a multi-slice interleaved manner to minimize crosstalk between slices. The first two volumes of each run were discarded to allow for scanner equilibration. The imaging parameters were as follows: echo time, 30 ms; field of view, 192 mm; in-plane resolution and slice thickness, 2 mm; repetition time, 2 s. Whole-brain high- resolution T1-weighted structural scans (1x1x1 mm) were acquired and coregistered with the participant’s mean EPI images. These images were averaged together to permit anatomical localization of the functional activations at the group level.

## *MRI data preprocessing*

Preprocessing was performed using the default settings of FMRIPREP software version 1.2.5 (Esteban et al., 2019). In this preprocessing workflow each T1-weighted (T1w) volume was corrected for intensity non-uniformity using N4BiasFieldCorrection v2.1.0 (Tustison et al., 2010) and then skull-stripped using antsBrainExtraction.sh v2.1.0 (using the OASIS template). Brain surfaces were reconstructed using recon-all from FreeSurfer v6.0.1 (Dale, Fischl, & Sereno, 1999), and the brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer-derived segmentations of the cortical gray-matter of Mindboggle (Klein et al., 2017). Spatial normalization to the ICBM 152 Nonlinear Asymmetrical template version 2009c (Fonov et al., 2011) was performed through nonlinear registration with the antsRegistration tool of ANTs v2.1.0 (Avants, Epstein, Grossman, & Gee, 2008), using brain-extracted versions of both T1w volume and template. Brain tissue segmentation of cerebrospinal fluid (CSF), white-matter (WM) and gray-matter (GM) was performed on the brain-extracted T1-weighted image using fast (Zhang, Brady, & Smith, 2001).

Functional data were slice time corrected using 3dTshift from AFNI v16.2.07 (Cox, 1996) and motion corrected using mcflirt (Jenkinson, Bannister, Brady, & Smith, 2002). This was followed by co-registration using bbregister (FreeSurfer v6.0.1) to the corresponding T1w image using boundary-based registration (Greve & Fischl, 2009) with 9 degrees of freedom. Motion correcting transformations, BOLD-to-T1w transformation and T1w-to-template (MNI) warp were concatenated and applied in a single step using antsApplyTransforms (ANTs v2.1.0) with Lanczos interpolation. Many internal operations of FMRIPREP use Nilearn (Abraham et al., 2014), principally within the BOLD-processing workflow. For more details of the pipeline see <http://fmriprep.readthedocs.io/en/latest/workflows.html>.

Frame-wise displacement (Power et al., 2014) was calculated for each functional run using the implementation in Nipype. After preprocessing, runs that had framewise displacement (FD) measures above threshold (0.2mm, FMRIPREP) on over 30% of frames were excluded. Runs that had above threshold FD on 12-30% of frames were included if visual analysis of the carpet plot did not reveal major distortion. Runs with FD below 12% of frames were kept. If subjects had more than three out of the nine total runs removed for excessive framewise displacement, they were excluded from the sample. These exclusion criteria resulted in 11 subjects being removed from our analysis due to excessive head motion – in addition to the three that withdrew before task completion. Within the 50 subjects kept for analysis 11 subjects had three runs removed, eight subjects had two runs removed, five subjects had a single run removed, and 23 subjects had no runs removed based on the head motion trial exclusion criterion.

## *MRI data analysis*

*GLM 1: Neural representations of decision value.* Using our preprocessed data, we conducted a general linear model (GLM) with first-order autoregression, as implemented in SPM12, in order to identify regions associated with decision value. This analysis proceeded in three steps. First, we estimated the model separately for each individual. Second, we calculated contrast statistics at the individual level. Third, we computed second-level statistics by carrying out one-sample t tests and correlations on the single-subject contrast coefficients.

The model consisted of six regressors of interest: R1–R3 were indicator functions beginning at onset of food on each trial and having a duration of the trial’s response time, modeled separately for NATURAL trials (R1), DECREASE trials (R2) and HEALTH trials (R3). Regressors R4–R6 consisted of parametric modulators of each indicator function representing the value of the participant’s preference (from Strong No to Strong Yes) for that trial type. The model also included motion parameters and session constants as regressors of no interest. To identify voxels in the vmPFC and dlPFC that were consistently associated with value across all three conditions, we calculated a contrast (C1) at the individual level, consisting of the combination of [R4 + R5 + R6]. To examine how activation in vmPFC and dlPFC varied overall as a function of condition, we also calculated subject-level images for NATURAL (R1) HEALTH (R2) and DECREASE (R3) conditions separately .

*GLM 2: Trial-specific beta series responses.* Although GLM 1 identified areas whose activation correlates with value, it cannot reveal whether those regions explain *independent components*  of the variance in behavioral responses. To do this requires a different approach, in which activation in each region is used to predict behavioral responses, after controlling for activation in other regions. For this approach, we used a method developed by Cosme et al. (2019), in which trial-by-trial responses from different brain regions are computed and then entered simultaneously into a multiple regression analysis. We thus used GLM 2 to extract these trial-level responses. This GLM consisted of 270 regressors of interest, consisting of a box-car function with an onset at the beginning of each trial and a duration of the subject-specific RT for that trial. All other details were as in GLM 1.

*Region-of-Interest of Analyses*

Based on GLM 1 described above, we constructed two *a priori* defined regions-of-interest (ROIs) consisting of 6mm spheres placed around the peak correlation with decision value (C1) in the vmPFC (centered at x = -6, y = 24, z = 18) and the dlPFC (centered at x = 40, y = 34, z = 18).

Using these two regions, we extracted contrast estimates for 1) overall response in each of the three conditions (GLM 1); and 2) trial-by-trial BOLD response for each subject, using the regression weights derived from GLM 2, normalized within each subject (Cosme et al., 2019).

*GLM 3:* To test whether regulation altered the sensitivity of stimulus-related value signals contained in the vmPFC and dlPFC to tastiness and healthiness, we estimated GLM 3, a model predicting trial-by-trial responses in each region for each subject and each condition separately with the following predictors:

|  |  |
| --- | --- |
|  | (3) |

where ROI*Foodi* represents trial-specific response in either dlPFC or vmPFC. To compare across conditions, and to correlate individual differences with neural activation, we performed statistical analyses using the subject-level slope terms for tastiness () and healthiness ().

*GLM 4.* To test whether regulation altered the sensitivity of behavior to the value signals contained in the vmPFC and dlPFC (i.e., response-related signals), we estimated a model for each subject and each condition separately with the following predictors of decision value on each trial:

|  |  |
| --- | --- |
|  | (4) |

To compare across conditions, and to correlate individual differences with neural activation, we performed statistical analyses using the subject-level slope terms for the vmPFC () and dlPFC ().

**Results**

**Behavioral Results**

*On-line effects of regulation*

We first sought to verify that participants’ behavior changed in a goal-consistent manner duringmoments of active cognitive regulation. To do this, we performed one-way repeated-measures ANOVAs with condition (NATURAL, HEALTH, DECREASE) as a fixed effect and three outcome measures as dependent variables: 1) average decision value within each condition, 2) subject-level slope terms for the influence of tastiness on decision value and 3) subject-level slope terms for the influence of healthiness on decision value (see Equation 1).

As expected, we found a significant effect of condition on average decision value (F2,98 = 44.5, *P* < .0001). Consistent with regulatory goals, the DECREASE condition resulted in lower decision values on average (M = 2.0±0.30 [s.d.]) compared to NATURAL (M = 2.3±0.37, paired-t49 = 7.37, *P* < .0001), with the HEALTH condition in between and significantly different from both (M = 2.2±0.28, both paired-t49 >3.73, both *P* < .001).

As expected, we also found a significant effect of condition on the influence on choice of both tastiness (F2,98 = 18.78, *P* < .0001) and healthiness (F2,98 = 59.06, *P* < .0001). Consistent with regulatory goals, tastiness influenced choices more strongly during NATURAL trials (mean *β =* 0.30±.15) compared to either HEALTH trials (mean *β =* 0.18±.14, paired-t49 = 5.25, *P* < .0001) or DECREASE trials (mean *β =* 0.18±.16, paired-t49 = 4.63, *P* < .0001), which did not differ significantly from each other (paired-t49 = .13, *P* = 0.81). We also found that healthiness influenced choices more strongly during the HEALTH condition (mean *β =* 0.24±.16) than either the NATURAL condition (mean *β =* 0.05±.11, paired-t49 = 7.93, *P* < .0001) or DECREASE condition (mean *β =* 0.053±.09, paired-t49 = 8.63, *P* < .0001), which did not differ from each other (paired-t49 = .16, *P* = .88).

To examine whether regulation required greater effort, we also compared average RTs across the conditions. As expected, we observed a significant effect of condition on RT (F2,98 = 13.45, *P* < .0001), with responses in both the HEALTH (mean RT = 1,404ms±297) and DECREASE (mean RT = 1,440±384) conditions taking significantly longer compared to NATURAL (mean RT = 1,322±298, both paired-t49 > 3.91, both *P* < .0001).

*Persistent effects of regulation*

We next examined the influence of cognitive regulation on changes in food liking from baseline (ΔLiking). We characterize a persistent effect as a systematic change in liking that occurs between the in-scanner cognitive regulation task and the post-scan liking rating. The mean time that elapsed between the viewing of a food stimulus in-scanner and the post-scan liking rating was about one hour (M = 57.01 minutes, SD = 8.65 minutes). In order to assess this potential effect, we first asked whether regulation (particularly the DECREASE condition) resulted in a *general* decreasein liking for *all* foods. Second, we asked whether regulation (particularly the HEALTH condition) resulted in an increase in the influence of healthiness (or decrease in the influence of tastiness) for foods appearing in that condition. To test for these persistent effects, we performed one-way ANOVAs with condition (NATURAL, HEALTH, DECREASE) as a fixed effect, and subject-level intercept (β0) and slope terms for tastiness (β1) and healthiness (β2) as the dependent measures (see Equation 2).

Interestingly, we observed non-significant differences among the conditions in the change in *overall* liking for foods (F2,98 =1.47, *P* = .24), where both DECREASE and HEALTH conditions showed non-significant changes in the expected direction (mean DECREASE = .37±0.66, mean HEALTH = 0.37±0.91) compared to foods in the NATURAL condition (mean = .50±1.06).

Similarly, although tastiness predicted greater increases in ΔLiking on average (mean = 0.385±0.155, F1,98 = 31.4, *P* < .0001), we observed little evidence that those changes varied as a function of condition (F2,98 = .12, *P* = .89.). Note that this lack of difference across conditions in persistent changes in concern for tastiness occurred in the context of strong decreases in the influence of tastiness during on-line, momentary, regulation.

In contrast, we observed significant differences among conditions in the extent to which healthiness predicted ΔLiking (F2,98 = 5.72, *P* < .005). As expected, follow-up t-tests indicated that healthiness predicted stronger increases in liking specifically for those foods that had appeared in the HEALTH condition (mean = .083±0.14) compared both to NATURAL (mean = .037±.12, paired-t49 = 3.4, *P* = .001) and DECREASE trials (mean β2 = .047±.13, paired-t49 = 2.45, *P* =.02), which did not differ from each other (paired-t49 = .65, *P =* .52). Thus, consistent with prior work (Boswell et al., 2018), health-focused regulation led to a significant increase in liking for healthier food targets that persisted beyond the moment of active regulatory focus.

**Neural Results**

*vmPFC and dlPFC correlate with decision value*

To identify regions-of-interest in the vmPFC and dlPFC, we conducted a general linear model in SPM identifying neural correlates of decision value at the time of choice (i.e. response of Strong No to Strong Yes during food choice, GLM 1, Contrast 1) across all three conditions. As expected, this analysis identified both the ventromedial prefrontal cortex (vmPFC) and the right dorsolateral prefrontal cortex (dlPFC) (P < .05, whole-brain corrected, Figure 1a,c and Table X). We therefore defined 6-mm spherical ROIs around the peak of activation in each region, which we used to extract parameter estimates for further analysis.

*Regulation-induced change in stimulus-related vmPFC repsonse.*

We began by asking whether regulation altered responses in the vmPFC in a goal-consistent way. First we asked whether overall activation in this region changed as a function of regulatory goal, using a one-way, repeated-measures ANOVA with condition (NATURAL, HEALTH, DECREASE) as a fixed effect, and average response in each condition as the dependent measure. Although we observed a comparatively weak effect of condition on overall response in the vmPFC (F2,98 = 2.00, *P* =0.14), follow-up planned comparisons confirmed that activation in the vmPFC was reduced in the DECREASE compared to NATURAL conditions (paired-t49 2.33, *P* = .02, Figure 1b, left). The comparison between DECREASE and HEALTH trials failed to reach significance (paired-t49 = 1.16, *P*  = .25).

Next, we investigated neural sensitivity of the vmPFC to tastiness and healthiness (Equation 3). Notably, the vmPFC showed a main effect of tastiness across all three condition (F1,98 = 11.33, *P* = .001), with no effect of condition on this response (Figure 1b, middle, F2,98 = .09, *P* = .92). In contrast, we observed no main effect of healthiness in the vmPFC (F1,98 = 1.57, *P* = .21), but did observe a marginally significant interaction effect of condition (F2,98 = 2.58, *P* = .08), meaning that [explain]. This was driven by a modest increase in sensitivity to healthiness in the HEALTH condition compared to both other conditions (both t49 > 1.97, both *P* < .06, see Figure 1b, right). Thus, responses in this region of the vmPFC showed goal-consistent but modest effects of cognitive regulation.

*Regulation-induced change in stimulus-related dlPFC response.*

We next turned to a similar set of analyses in the dlPFC. This analysis suggested that regulation produced a significant and selective decrease in response in this region during DECREASE trials (F2,98 =5.34, *P* = .006) compared to NATURAL and HEALTH conditions (both paired-t49 > 2.86, both *P* < .006, Figure 1d, left). However, in contrast to the vmPFC, we observed no main effect of tastiness in the dlPFC (F1,98 = 1.19, *P* = .28), nor was there a significant effect of condition on tastiness response (F2,98 =.42, *P* = .66, Figure 1d, middle). Finally, we investigated neural sensitivity of the dlPFC to healthiness. This analysis showed a main effect of healthiness in this region (F1,98 = 7.12, *P* = .009) qualified by a significant interaction with condition (F2,98 = 6.23, *P* = .003), meaning that [explain how to interpret]. Follow-up analyses suggested that the dlPFC showed significantly greater responses to healthiness during the HEALTH condition compared to both NATURAL and DECREASE trials (Figure 1d, right, both paired-t49 > 2.79, both *P* < .008).

*Regulation alters the independent contributions of vmPFC and dlPFC to behavior*

The results above suggest two things. First, both the vmPFC and the dlPFC showed regulation-consistent changes in the DECREASE and HEALTH conditions, though these effects were somewhat more reliable in the dlPFC compared to the vmPFC. Second, the vmPFC showed a specific, goal-inconsistent sensitivity to tastiness that did not vary by regulatory goal. These results are consistent with past work (Hare et al., 2011; Hutcherson et al., 2012; Tusche & Hutcherson, 2018), and led us to predict that a possible route to regulatory success might be to decrease the influence of the vmPFC on choice behavior, and to increase the influence of the dlPFC. To test this possibility, for each subject we conducted regression analyses in which we predicted trial-by-trial decision values simultaneously from trial-by-trial variation in vmPFC and dlPFC response (Equation 4), controlling for subject-specific tastiness and healthiness ratings. We then conducted repeated-measures one-way ANOVAs with condition as a fixed effect and subject-level influence of dlPFC and vmPFC on choice as dependent measures.

We observed a striking alteration in the extent to which vmPFC and dlPFC predicted behavioral responses across the three conditions (Figure 2). Choice behavior showed a significant difference in sensitivity to signals carried in the vmPFC as a function of condition (F2,98 = 5.62, *P* = .005), driven by a significantly stronger predictive relationship in the NATURAL condition compared to both DECREASE (paired-t49 = 3.59, *P* = .001) and HEALTH trials (paired-t49 = 1.96, *P* = .06). The dlPFC displayed the opposite pattern, showing marginally greater correlations with choice compared to NATURAL in both the DECREASE condition (paired-t49 = 1.98, *P* = .053) and HEALTH conditions (paired-t49 = 1.72, *P* = .09), although the repeated-measures ANOVA interaction effect fell short of significance (F2,98 = 2.06, *P* = .13). Thus, we found evidence of regulation-related shifts in the extent to which vmPFC and dlPFC appeared to uniquely predict choice behavior.

*Neural predictors of the transience of regulatory changes in preference*

These results suggest that subjects may have adopted a strategy in which they used value signals in the dlPFC to compensate for a failure of vmPFC value signals to adapt fully to the regulatory goal, which required a decreased focus on tastiness. While such a strategy might be successful in the moment, we suspected that it might also result in transient, rather than persistent, changes in food preference. To test this idea, we asked whether goal-consistent changes in the vmPFC or dlPFC predict the persistence or transience of regulatory effects. We speculated that individuals demonstrating successful, goal-consistent changes in the vmPFC might have more persistent effects of regulation, while individuals demonstrating evidence of goal-consistent responding in the dlPFC might show comparatively more transient effects of regulation.

Our hypothesis was partially confirmed. We observed a marginal *negative* correlation between decreases in the dlPFC in the DECREASE compared to NATURAL condition and the extent to which overall liking for foods in the DECREASE condition were suppressed from baseline (Pearson’s *r48* = .26, *P* = .03, one-tailed, Figure 4b). We also observed a marginal *negative* correlation between dlPFC sensitivity to healthiness in the HEALTH vs. NATURAL conditions and the extent to which healthiness caused an increase in liking for foods from baseline (Pearson’s *r48* = .27, *P* = .03, one-tailed, Figure 4c). However, no relationship was observed between response in the vmPFC and the persistence of regulatory effects (all *P* > .53).

*Neural correlates of regulatory effort*

Our results suggest that the dlPFC might be brought on-line temporarily as a way to accomplish regulatory goals. Our theoretical model suggests one further prediction: that this effect might require additional effort to accomplish. Thus, as an exploratory analysis, we asked whether individual differences in RT between the three conditions, which may serve as a proxy for effort, correlated with the extent to which the dlPFC showed goal-consistent change in response. Although we observed no correlation between the increase in RT in the HEALTH condition and response in the dlPFC, we did observe a significant negative correlation between increased RT in the DECREASE compared to NATURAL conditions and the extent to which responses in the dlPFC decreased during this condition (Pearson’s *r48* = -.39, *P* = .006). Thus, the longer a participant took to choose, the more likely they were to show evidence of a goal-consistent effect of regulation in the dlPFC.

**Discussion**

These results advance our understanding of cognitive self-regulation of dietary choice in several ways. First, they confirm the important roles of both the vmPFC and the dlPFC in value-based decision making. Second, they support a model in which distinct regulatory goals can produce distinct, goal-consistent changes in stimulus-related response in both the vmPFC and dlPFC, although such effects were more prominent in the dlPFC. Third, they corroborate other accounts (Hutcherson et al.., 2012; Tusche & Hutcherson, 2018) suggesting that in contexts where vmPFC shows goal-inconsistent responses (i.e., representing tastiness when goals dictate otherwise), the dlPFC may assume greater responsibility not only for representing stimulus values in an appropriate way, but also for driving the preferences expressed in overt behavior. Finally, they provide evidence about the nature of this compensatory response. It may, in some cases, require extra time to implement, and is associated with evidence that the effects of regulation fail to endure beyond the moment of active regulatory focus. These results raise a number of important questions, and have several intriguing implications for our understanding of dietary self-regulation in both the short and long term.

One of the key questions implicated by this research concerns the nature of value signals contained in the vmPFC and dlPFC. In one popular view, the vmPFC serves as an integrative hub for attribute-specific value signals received from other areas. In this view, the vmPFC integrates different attributes weighted relative to their current goal values (Basten, Biele, Heekeren, & Fiebach, 2010; Hutcherson, Montaser-Kouhsari, Woodward, & Rangel, 2015; Lim, O'Doherty, & Rangel, 2013), with the dlPFC acting either as an input to the vmPFC for particular attributes, or as a modulator of the weights given by the vmPFC to incoming attribute signals (Hare, Camerer, & Rangel, 2009). In contrast, other work suggests that the dlPFC might represent an independent input into the process of action selection (Hutcherson et al., 2012).

Our findings are more in line with the latter account. In particular, trial-specific responses in the vmPFC and dlPFC predicted the subject’s behaviorally expressed preference on that trial, over and above other factors like subjectively perceived tastiness and healthiness. However, they did so in different contexts. Signals in the vmPFC contributed to choice more strongly under conditions of naturalistic response, but ceased to do so consistently when participants attempted to regulate their decisions. This was true regardless of whether the goal was simply to reduce craving for all foods generally, or instead to focus on approaching healthy foods and avoiding unhealthy foods. In contrast, we observed more modest, though suggestive changes in the opposite direction for the dlPFC. This area contributed less to the final choice in the absence of regulation, and contributed more strongly during moments of active regulatory focus.

Our results extend other recent work suggesting that control may in some cases involve an arbitration between independent value signals. For example, in the domain of model-free vs. model-based choice, research suggests that regions of the ventrolateral prefrontal cortex may contribute to this arbitration function between different value systems (Lee, Shimojo, & O’Doherty, 2014). While it remains to be seen whether the vlPFC plays a similar role here, we note that the area of vlPFC identified as the arbitrator in previous work strongly resembles the areas of vlPFC activated in several previous studies of cognitive self-regulation of food choice (e.g., Hutcherson et al., 2012) and emotion regulation (Kohn et al., 2014). Notably, this region was also more active in this study during regulation compared to naturalistic choice (data not shown). Future work will be needed to establish a causal link between functions of the vlPFC and arbitration between vmPFC and dlPFC signals observed here.

When interpreting our work we feel it is important to keep in mind what we see as a number of meaningful limitations. The central consideration in our view is the validity of the experimenter-imposed regulation conditions; while state induction is a fairly standard technique, it is very difficult to know whether our manipulation worked as intended. In particular it seems naïve to rule out the potentially large role of demand effects present in the laboratory context. We could expect that there is a heterogeneity of strategies employed by subjects that account for behavioral changes in the regulatory tasks, some of which are unaligned with the regulatory conditions we are attempting to examine. A second weakness in our experimental design is the fact that we only collected attribute ratings for the tastiness and health of each food after the scan (as opposed to liking ratings, which were collected pre and post). While this is a standard procedure in the field, and we ourselves have conducted studies confirming the stability of attribute ratings pre and post task, this decision forces us to assume stability of attribute rating. If this assumption is wrong, then it means we could be misstating the variance explained in pre/post liking by changes in attribute weights in our regression models. We are also aware that the time period over which the persistent effects of our manipulation are tested (ca. 60 minutes) is much too short to be meaningful in a real-world context. Testing the durability of the effect over longer timespans would help make clear whether our manipulations could be beneficial outside of the laboratory.

Our results present one answer to why diets may not last: if regulation operates in part by temporarily recruiting the dlPFC to represent stimulus values in a goal-consistent way, but requires effort to maintain, then a loss of focus on the regulatory task may result in a rebound of previous preferences. Indeed, in our study, individuals who showed the strongest goal-consistent stimulus representations in the dlPFC during regulation were also the *least* likely to maintain the effects of regulation on post-regulation preferences. But this result also raises an important question for further research: if recruitment of the dlPFC predicts a failure of regulatory efforts to last beyond the moment of active focus, what mechanisms predict enduring change? In our study, we saw evidence that a focus on healthiness in the moment may result in increases in the value of healthy foods afterwards. We had predicted that the changes in the vmPFC might correlate with such effects, but they did not. One possibility is that more sophisticated, multivariate analyses might yield clearer correlates of enduring change. Another possibility is that lasting change might result from connectivity between value regions and regions associated with memory and reward learning (e.g., hippocampus and ventral striatum: Gerraty et al., 2014; Wimmer & Shohamy, 2012). Future work will be needed to test these ideas.

Finally, although we focused here on the vmPFC and dlPFC, based on a plethora of work implicating these two regions in the cognitive self-regulation of value, our research suggests the potential utility of considering a larger set of potential players. For example, other regions, including orbitofrontal cortex, ventral striatum, and posterior cingulate cortex, also correlate with decision values at the time of choice (Clithero & Rangel, 2013). Perhaps each of these regions also plays a unique role in regulatory success under the right circumstance. Given the multitude of possible strategies people might use to regulate their evaluative responses (Gross, 2015), future work should take a more global perspective on this important issue.

SUPPLEMENATARY

* Text for subject state induction directions in all three conditions (R2.5)

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**Figure Captions**

**Figure 1.** Task design. Participants first completed a set of liking ratings for 270 foods. They then completed a cognitive regulation task, in which participants were asked to decide whether or not to eat foods that appeared in one of three instructed regulation conditions (Respond Naturally, Focus on Healthiness, Decrease Desire). Following completion of the regulation task, participants again rated their preference for all foods, allowing us to assess the effects of regulation on change in liking from baseline to post-task.

**Figure 2.** Regulatory effects of stimulus-related responses in the vmPFC and dlPFC. a) vmPFC was correlated with overall decision value at the time of choice (image thresholded at *P* < .00001, uncorrected). The green circle identifies the ROI used to generate the plots to the right. b) Responses in the vmPFC overall (left) and as a function of food tastiness (middle) and healthiness (right). c) dlPFC was also correlated with overall decision value at the time of choice. The green circle identifies the ROI used to generate the plots to the right. D) Responses in the dlPFC overall (left) and as a function of food tastiness (middle) and healthiness (right). Error bars indicate s.e. of the mean. + *P* < .06 \* *P* < .05 \*\* *P* < .01

**Figure 3.** Prediction of decision value responses at the time of choice in vmPFC (a) and dlPFC (b). Error bars indicate s.e. of the mean. + *P* < .09 \* *P* < .05 \*\* *P* < .01

**Figure 4.** Neural correlates of regulation induced changes in preferences. a) Goal-consistent decreases in activation in the dlPFC during DECREASE compared to NATURAL trials *negatively* predicted decreases in liking from baseline to post-regulation. b) Goal-consistent increases in the correlation of the dlPFC with healthiness in HEALTH compared to NATURAL trials *negatively* predicted the extent to which healthiness influenced post-task changes in liking.