# Eating less or more – Mindset induced changes in neural correlates of pre-meal planning

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## Abstract

Obesity develops due to an imbalance between energy intake and expenditure. Besides the decision about what to eat, daily energy intake might be even more dependent on the decision about the portion size to be consumed. For decisions between different foods, attentional focus is considered to play a key role in the choice selection. In the current study, we investigated the attentional modulation of portion size selection during pre-meal planning. We designed a functional magnetic resonance task in which healthy participants were directed to adopt different mindsets while selecting their ideal portion size for lunch. Compared with a free choice condition, participants reduced their portion sizes when considering eating for health and when planning to eat with pleasure, which was accompanied by increased activity in left prefrontal cortex and left orbitofrontal cortex, respectively. When planning to be full until dinner, participants selected larger portion sizes and showed increased activity in left insula. These results provide first evidence that also the cognitive process of pre-meal planning is influenced by the attentional focus at the time of choice, which could provide a key opportunity for influencing the control of meal size selection by mindset manipulation.

## 1. Introduction

According to the World Health Organization, worldwide obesity has more than doubled since 1980 and in 2014 more than 1.9 billion adults were estimated to be overweight (WHO 2016). Understanding factors that lead to obesity are of utmost importance as obesity is associated with diseases like diabetes and cardiovascular disease and thereby reduces average life expectancy (Haslam et al. 2005; Pischon et al. 2008). Obesity develops due to an imbalance between energy intake and expenditure (Westerterp 2010). A determining factor of our energy intake is not only the decision about what we eat, but maybe more importantly the decision about the size of the meals that we consume. In this regard, trends in obesity in the US have been associated with increasing portion sizes (Labbe et al. 2017). A main focus in understanding portion size selection has been to investigate the processes that generate increasing fullness during a meal (Blundell et al. 1987; Hetherington 1996). In the last decade, however, observations of natural eating behavior in humans highlight the importance of pre-meal planning, the decision of how much to eat before a meal begins (refer to review Brunstrom (2014)). This is supported by the observation that we tend to 'plate clean', to consume the total amount of food on our plate (Wilkinson et al. 2012). Furthermore, it was shown that humans not only have particular expectations about the tastiness or healthiness of foods, but also about their satiating effects (Brunstrom et al. 2008; Brunstrom et al. 2009; Wilkinson et al. 2012). The 'expected satiation' of a specific food is related to its energy density and will strongly influence the energy content of the selected portion size (Brunstrom et al. 2008). Wilkinson et al. (2012) even suggested that expected satiation might be a more important determinant of meal size than palatability. However, little is known about how these factors are integrated during pre-meal planning and about the neural correlates involved in these decisions.

For decision making between complex options that depend on and differ in multiple attributes (e.g. expected satiation, healthiness or tastiness of a meal), the brain is assumed to compute subjective values for all of these options by assigning values to the individual attributes and integrating them (Bettman et al. 1998). These integrated subjective values are then compared to make a choice (Glimcher et al. 2004; Rushworth et al. 2009; Rangel et al. 2010). The ventromedial prefrontal cortex (vmPFC) has been shown to be highly involved in these computational processes for a wide range of qualitatively different choice conditions (Bartra et al. 2013; Clithero et al. 2014).

It has been suggested that integration of the stimulus attributes depends on the attention assigned to them at the time of choice (Shimojo et al. 2003; Krajbich et al. 2010) and that the attentional focus likely varies within and across individuals (Roefs et al. 2015). The individuals' so called 'mindsets' can influence the way they evaluate options and make choices. For the decision between different food items, several functional magnetic resonance imaging (fMRI) studies show that the number of healthy choices increases when the attentional focus is directed to the health aspects of the foods (Hare et al. 2009; Hare et al. 2011a; Bhanji et al. 2012; Enax et al. 2015). Variations in attentional focus between individuals (Hare et al. 2009) and as a function of exogenous attention cues (Hare et al. 2011a; Enax et al. 2015) is associated with increased activity in the dorsolateral prefrontal cortex (DLPFC), a region known to be important in the cognitive control of behavior in general (Miller et al. 2001). The authors further suggested that the DLPFC mediates the behavior change by increasing the inclusion of healthiness attributes into the computation of the subjective value signals in the vmPFC.

In the current study, we aimed to explore behavioral responses and neural processes during pre-meal planning. In particular, we investigated whether different mindsets are associated with altered activity in certain brain areas during pre-meal planning and whether this effects the selection of portion sizes by influencing the integration of different stimulus attributes, namely expected satiation, healthiness and tastiness of a specific food.

In order to investigate the neural correlates associated with the selection of a portion size for lunch during different mindset instructions, we performed an fMRI study. Participants were asked to select their ideal portion size in a free-choice condition without further instructions (baseline), in consideration of health consequences (healthiness mindset), when they ate with pleasure (pleasure mindset) and when they ate to be full until dinner (fullness mindset). These mindsets were selected as we consider them to be important factors that moderate portion size selection.

For each of these mindsets, we expected changes in portion size selection and activity increases in mindset specific brain areas when compared to the baseline condition. More specifically, we hypothesized that participants would select smaller portion sizes and show increased activity in left DPLFC (according to Hare et al. (2009)) for the healthiness mindset. For the fullness mindset, we anticipated increased portion sizes and increased activity in the insula based on its role in interoceptive and satiation processes (for review refer to Frank et al. (2013)). Finally, for the pleasure mindset we had no directed hypothesis for the portion size selection, but expected an increase in activity in the orbitofrontal cortex (OFC) as the main integrative region for pleasure evaluation (for reviews refer to Kringelbach (2005); Rolls (2015)).

## 2. Material and Methods

### 2.1. Participants

23 young, healthy, and lean adults with no self-reported eating disorder, diabetes, or vegetarian/vegan diet participated in the study. One participant had to be excluded due to technical problems, one due to not finishing his meal and failing to provide answers during the feedback phase, one due to having a BDI-II (German version of the Beck depression inventory) (Hautzinger et al. 2006) score of 24 (moderate depression) and two due to selecting bigger portion sizes than available already in the baseline condition. The mean age of the remaining 18 participants (9 women / 9 men) was 24.6 (range: 18-31) years and the mean body mass index was 21.8 (range: 19.5-24.0) kg/m². All participants were right-handed and had normal or corrected-to-normal vision (contact lenses, MR compatible glasses). Written consent was obtained prior to the study. The study was approved by the Ethics Committee of the Medical Faculty of the University of Tübingen.

### 2.2. Stimuli

Stimuli were drawn from a database of different food stimuli, photographed in systematically varying portion sizes and on a standard background. As described in Brunstrom and Rogers (2009), the smallest portion size for each food was 20 kcal and then increased by 20 kcal for each picture up to 1000 kcal (resulting in 50 pictures per food). For our study, we selected 10 meals that are also common in Germany. For the fMRI task, we reduced the sets to 10 pictures per food, starting with a portion size of 100 kcal and increasing portion sizes in 100 kcal steps to 1000 kcal. In all rating tasks, the foods were presented in 500-kcal portions. The type and energy density of the foods are provided in Table S1.

### 2.3. Study design

Participants were instructed to follow an overnight fast of at least 12 h and to have a normal breakfast between 7.30 and 8.00 am at home on the recording day, and then refrain from eating and drinking anything else except water until arriving in our lab at 10.30 am.

Before the fMRI scanning session, participants were familiarized with the experimental procedure and the associated stimuli. First, each meal was displayed in turn on a laptop. In order to familiarize themselves with the meals and respective portion sizes, participants were instructed to decrease and increase the portion sizes and to select the portion size that they wanted to consume right now. Secondly, they also practiced the fMRI paradigm using a set of meals that were not included in the main task. Their weight and height was then measured and they indicated their current hunger on a 10 cm visual analog scale (VAS; 0: not hungry at all, 10: very hungry).

The fMRI scanning session (described below) started at around 11.15 am and lasted for around 1.5 h. Participants then provided a blood sample for standard blood parameters and the determination of glucose and HbA1c levels. All of the participants had a glucose level of <100 mg/dl and a HbA1c level of <37 mmol/mol (<5,6%) indicating that they were moderately fasted and had no diabetes.

While preparing their lunch, participants were asked to indicate the healthiness, tastiness, and expected satiation of each meal on a laptop, and they reported their current hunger again on the VAS. Healthiness and tastiness were measured with a scale of 1-5 with 1 indicating very unhealthy/very bad taste and 5 indicating very healthy/very good taste for the 500 kcal portions. Expected satiation was measured as described in Brunstrom and Rogers (2009) with a 500 kcal portion of Spaghetti Bolognese as the ‘standard’ food.

At around 1-1.15 pm, all participants received Spaghetti Bolognese (Barilla Bolognese neu (90kcal/100g), Barilla Spaghettoni no.7 (359kcal/100g dry weight)) in the portion size that they selected during the fMRI task. Participants were left alone to finish their meal for around

15 min (as long as they needed). They were again asked to report their current hunger and indicate whether the amount just eaten was a) too much, b) too little, c) about right, d) exactly right and whether the taste was a) very good, b) good, c) neutral, d) not good, e) not good at all.

To make the selection more realistic, participants had to stay in the lab for another hour. Over this period they completed several questionnaires. Finally, participants again indicated their current hunger and eating in the relative absence of hunger was assessed in an ad libitum snack test presented as a 'taste test' as described in Thienel et al. (Thienel et al. 2016). This test will not be analyzed in the framework of this study.

### 2.4. Task design

As described above, we used 10 different meals in 10 different portion sizes for the fMRI task. During each task block, every meal was shown 3 times, which resulted in 30 trials per block. Each trial started with the presentation of a random meal. To control for anchoring effects, randomization of its portion size was performed in a controlled manner. Each meal started once in the lower range of portion sizes, once in the middle and once in the upper range.

- Insert Figure 1 here -

Upon each stimulus presentation, participants were required to decide whether they wanted to increase or decrease the portion size (Figure 1). They were instructed to respond with their right thumb; pressing a right button increased the portion size and pressing a left button decreased the portion. The picture was shown until the participants responded, then the next bigger or smaller portion size was shown after a jittered (1-2s) inter-stimulus fixation cross.

After the initial decision to increase or decrease the portion size, participants were only allowed to go on in the same direction until they reached their desired portion size (pre decisions). Before selecting the final portion size, they were allowed to change directions once if needed. When they reached the desired portion size, participants implemented their decision by pressing the middle button (final decision). The selected portion size was then shown again for 2s and participants were asked to indicate whether they were satisfied with their selection or not by using their right thumb to press an upper button for ‘yes’ and a lower button for ‘no’ (feedback). If the participants still wanted to increase or decrease when there was no bigger or smaller portion size, respectively, the last available portion size was shown again and they were also asked whether they were satisfied with it or not (feedback). For the final analysis, we only included final decisions with an active and satisfactory selection of a portion size. Trials were separated by a fixation cross of random duration (uniform: 2-6 s; additionally we included 3 null events per block of 12 s each).

As the task was mainly self-paced, some participants were faster as others to complete the requested 30 trials. Participants were allowed 10.5 min to complete the task. If they needed less time to complete the 30 trials, then they were kept busy with dummy trials until the end of the recording. These trials were not used for later analysis. During scanning, stimuli were presented visually using Presentation® (Neurobehavioural Systems, Inc., Albany, CA.) and were displayed using a video projector that illuminates a rear projection screen at the end of the head-bore. Participants viewed the stimuli through an adjustable mirror attached to the head coil.

Each participant completed the task 4 times. Each time they received a different instruction to induce a specific mindset. During each of the 4 task blocks, participants had to select for each meal the portion size that they wanted to eat for lunch that day. For the baseline condition, they would not receive any additional instruction. For the other three conditions, they were instructed to imagine selecting their portion sizes under certain considerations. To induce a pleasure mindset, they were told to select a portion size if they were eating with pleasure, for the healthiness mindset if they were considering health aspects and for the fullness mindset if they were planning to be full until dinner. Except for the baseline condition, all other conditions were pseudo-randomized to avoid order effects. In addition, participants were informed that after completing the task, one trial from the baseline condition would be randomly selected and implemented to make choices more realistic. For lunch, they would then receive the meal (actually all participants were served Spaghetti Bolognese, however, they did not know that) in the portion size that they selected during that trial.

### 2.5. Behavioral analysis

Decision times were compared across mindsets by calculating mean reaction times for all decisions (pre and post) for each mindset and each participant separately and by entering them in a repeated measures ANOVA with the within factor mindset (4 levels: baseline, fullness, pleasure, healthiness). Post hoc tests were Bonferroni corrected.

The selected portion size of each meal for each participant was defined as the median of the responses (up to 3 per food) per task block. If participants repeatedly wanted to select bigger portion sizes than available in the baseline condition, they were excluded. If participants only wanted to select a bigger portion size for up to 3 meals in the fullness mindset (3 participants, 1x3 meals, 2x1 meal), then we included them and replaced the missing value for the portion size of that meal with the largest available amount of 1000 kcal.

For each meal in the expected-satiation task, we derived a ‘satiation ratio’ by dividing the size of the standard (500 kcal) by the size of the selected comparison (in kcal) (the satiation ratio of the standard was recorded as 1).

On a group level, we were interested in whether we could replicate findings of Brunstrom and Rogers (2009) for the baseline condition in ideal portion size selection, energy density, expected satiation, tastiness and healthiness rating. Thus, for each of the measures obtained from participants’ responses, we additionally converted each participant’s data into a set of Z scores to control for differences in the average response between participants. For each measure and test food, we then calculated a mean Z score. Two-sided Pearson correlations were then calculated to assess the relationship between the measures.

For the investigation of the induced mindset effects, we averaged over the meals to obtain one value per participant and condition. The meal size selection was compared to the selection in baseline for each mindset separately in a repeated measures ANOVA with the within factor condition (2 levels: baseline, respective mindset) and the between factor gender (2 levels: men, women). Gender effects were further investigated with two-way independent t-tests to clarify directionality.

Finally, we used multilevel linear modeling to investigate the influence of the meal related ratings (healthiness, tastiness, expected satiation) on portion sizes during the different mindsets. Multilevel linear modeling was used as meals and ratings were nested within participants (multiple observation and non-independence between participants) and to account for individual differences. We calculated a separate model for each rating and each mindset. In these models, portion sizes were the level 1 units of analysis, and participants the level 2 units of analysis. Accordingly, expected satiation, tastiness and healthiness ratings were level 1 factors. To account for individual differences in mean portion size selection, we allowed random intercepts. Parameters were estimated using maximum likelihood criteria.

Behavioral data was analyzed with the software package SPSS 23.0 (SPSS Inc., Illinois; USA). All data are presented as unadjusted mean ± standard error of the mean. P-values $< 0.05$ were considered significant.

### 2.6. fMRI data acquisition and preprocessing

Whole brain fMRI data were obtained by using a 3.0 T scanner (Siemens MAGNETOM Prisma, Erlangen, Germany) equipped with a 20 channel head coil. Each block consisted of 312 scans (repetition time = 2 s, echo time = 30 ms, matrix 64 x 64, flip angle 90°, voxel size 3 x 3 x 3 mm$^3$, 30 slices), and the images were acquired in ascending order. Furthermore, a high-resolution T1-weighted anatomical image (magnetization-prepared rapid gradient echo (MPRage): 176 slices, matrix 256 x 256, 1 x 1 x 1 mm³) of the brain was obtained. In addition, we acquired a static field map to unwarp geometrically distorted functional scans. Participants were scanned while lying in a supine position with their head stabilized by foam padding around their head within the head coil. In addition, we acquired a resting state and DTI measurements, which are not analyzed in the framework of this study.

Preprocessing and statistical analysis of the fMRI data were performed using SPM12 (Wellcome Trust Centre for Neuroimaging, London, UK). Images were realigned and resliced to the first image. Unwarping in the phase-encoding direction (anterior-posterior) was performed using the pre-calculated voxel displacement map. A mean image was created and co-registered to the T1 structural image. The anatomical image was normalized to Montreal Neurological Institute (MNI) space using the segmentation approach. The resulting forward deformation fields were used to normalize the functional images (voxel size 3 x 3 x 3 mm³). Finally, the normalized images were smoothed with a 3-dimensional isotropic Gaussian kernel [full width at half maximum (FWHM): 8 mm]. FMRI data were highpass filtered (cutoff period 128s) and global AR(1) auto correlation correction was performed.

### 2.7. fMRI data analysis

fMRI data were analyzed in an event-related design using the general linear model (GLM) approach in a two-level procedure. On the first level in the single participant models, responses to stimuli were modeled as events and convolved with a canonical hemodynamic response function composed of two gamma functions (Friston et al. 1998). The temporal derivatives were used as an additonal regressor to capture possible differences in the latency of the peak amplitude of the blood oxygenation level-dependent (BOLD) signal. To account for variance caused by head movement, six realignment parameters were included as additional regressors in the model.

The data from each participant were analyzed by using linear regression between the observed event-related EPI signals and regressors that represent the individual trial events (pre decisions (increase/decrease), final decisions (final selection of portion size), feedback trials and a regressor of no interest including the dummy trials and those decisions with which the participants were not satisfied). The individual contrast images from each participants (final decision: final decision vs pre decisions of all sessions, fullness: final decisions during fullness mindset vs baseline condition, pleasure: final decisions of pleasure mindset vs baseline condition, healthiness: final decisions of healthiness mindset vs baseline condition) were then entered into separate second level analyses using one-sample t-tests. Effects were considered significant using a primary threshold at peak level of $p<0.001$ uncorrected and a whole-brain family wise error correction (FWE) of $p<0.05$ at cluster level for multiple comparisons. In addition, we performed region of interest (ROI) analysis with FWE correction of $p<0.05$ at peak level. ROIs were constructed with the WFU Pickatlas (v2.4) (Maldjian et al. 2003; Maldjian et al. 2004). For the healthiness mindset, we selected a functional ROI of left DLPFC based on Hare et al. (Hare et al. 2009) (sphere of 10 mm with MNI center coordinates: -48 15 24). One participant was identified as an outlier and excluded from the analysis for this contrast (more than 3 standard deviations apart from the mean). For the pleasure and fullness mindset, we selected anatomical ROIs based on the aal atlas (Tzourio-Mazoyer et al. 2002) implemented in the WFU Pickatlas. For the fullness mindset, we selected left and right insula. For the OFC in the pleasure mindset, we selected left and right inferior orbital frontal gyrus as an ROI. This was based on the description of spatially distinct subregions of the OFC and our expectation of changes in the processing of pleasure (for reviews refer to Kringelbach (2005); Zald (2009); Rushworth et al. (2011); Rolls (2015)).

We also tested for behavioral correlations between the change in portion sizes between the mindsets and baseline and difference in activity during the final selection between the respective mindset and the baseline condition. Clusters with a significance level of $P<0.001$

uncorrected and cluster size >5 and within a sphere of 20 mm around the peak voxel of the significant clusters in the respective mindset contrasts are reported.

In addition, we tested for parametric modulations with the behavioral expected satiation, healthiness and tastiness ratings. For this, we converted the measures into Z scores and included them as a linear parametric modulator for the final decision regressor in the GLM described above. The individual contrast images from each participant for each parametric modulator and each mindset were then entered into separate second level analyses using full factorial designs. For each rating, we report the main effect of the parametric modulator across all conditions. In addition, we explored whether the contrasts of the rating associated mindset against the other mindsets showed increased parametric modulation in the respective mindset particularly in vmPFC. Effects were again considered significant using a primary threshold at peak level of $p<0.001$ uncorrected and a whole-brain family wise error correction (FWE) of $p<0.05$ at cluster level for multiple comparisons. In addition, we performed region of interest (ROI) analysis with FWE correction of $p<0.05$ at peak level for the vmPFC. As described above, an anatomical ROI based on the aal atlas (Tzourio-Mazoyer et al. 2002) implemented in the WFU Pickatlas (Maldjian et al. 2003; Maldjian et al. 2004) including left and right medial orbitofrontal gyrus was selected.

## 3. Results

### 3.1. Behavioral Results

Participants spent on average 1.14±0.08s on a decision with final decisions taking longer than pre decisions (1.38±0.11s vs 1.06±0.07s; t(17)=5.45, p<0.001). Furthermore, decision times were significantly different between mindset conditions F(1,17)=5.69, p=0.002. Post hoc tests revealed that this was due to significantly longer reaction times in the baseline condition only.

*Average expected satiation, energy density and ideal portion size selection during baseline condition*

As expected and reported previously (Brunstrom et al. 2009), higher energy density of a meal was associated with lower expected satiation (Figure S1; r=-0.821, p=0.004). In addition, expected satiation was also related to the portion sizes of the meals selected in the baseline condition (Figure S1; r=-0.812, p=0.004)). Finally, portion size selection during baseline condition was neither significantly related to tastiness ratings (r=0.554, p=0.097), nor healthiness ratings (r=-0.297, p=0.405).

*Mindset induced changes on portion size selection*

- Insert Figure 2 here -

We observed a significant main effect of condition for all three induced mindsets (fullness: F(1,16)=35.18, p<0.001; pleasure: F(1,16)=11.31, p=0.004; healthiness: F(1,16)=71.06, p<0.001). Whereas participants selected significant larger portion sizes during the fullness mindset, they reduced their portion sizes in the pleasure and healthiness mindset in comparison to the baseline condition (Figure 2). Furthermore, we observed a significant main effect of gender for all three mindsets (fullness: F(1,16)=16.33, p=0.001; pleasure: F(1,16)=7.60, p=0.014; healthiness: F(1,16)=12.09, p=0.003) and a significant interaction between condition and gender for the pleasure (F(1,16)=6.05, p=0.026) and the healthiness mindset (F(1,16)=13.20, p=0.002). Figure S2 shows that male participants selected significantly larger portion sizes in the baseline (t(16)=4.17, p=0.001) and the fullness mindset (t(16)=3.40, p=0.004) compared with the female participants and on trend level in the healthiness (t(16)=2.11, p=0.051), but not in the pleasure mindset (t(16)=0.53, p=0.61). More specifically, Figure S2 shows that the decrease in portion size selection between baseline and respective mindset condition was stronger in male participants in the pleasure (t(16)=-2.46, p=0.026) and in the healthiness mindset (t(16)=-3.63, p=0.002), but not in the fullness mindset (t(16)=-0.06, p=0.96).

*Multilevel linear modeling*

Multilevel linear modeling showed that expected satiation (b=-2.40, t(166.32)=-5.70, p<0.001) and tastiness ratings (b=0.53, t(166.17)=4.93, p<0.001), but not healthiness ratings (b=-0.21, t(165.70)=-1.84, p=0.067) significantly predicted meal size selection during the baseline condition. This was also observed for the fullness and the pleasure mindset, although the influence of the tastiness ratings seemed to be slightly reduced during the fullness mindset (fullness mindset: expected satiation (b=-2.67, t(164.77)= -7.29, p<0.001), tastiness (b=0.28, t(165.28)=2.72, p=0.007), healthiness (b=-0.08, t(164.71)=-0.75, p=0.46); pleasure mindset: expected satiation (b=-2.51, t(167.14)=-5.89, p<0.001), tastiness (b=0.62, t(167.37)=5.76, p<0.001), healthiness (b=0.01, t(167.39)=0.10, p=0.92)). Finally, for the healthiness mindset, again expected satiation (b=-2.10, t(168.60)=-5.94, p<0.001) and to a seemingly lesser extent tastiness ratings (b=0.23, t(1670.21)=2.34,p=0.021) predicted portion size selection, but now also the healthiness ratings showed a significant effect (b=0.45, t(168.73)=4.91, p<0.001).

## 3.2. Imaging Results

*Final Decision*

When participants decided to finally select a portion size in comparison to decisions to further increase or decrease a portion size, we observed an increased response in clusters including the anterior cingulate cortex (ACC) and the left pre- and postcentral gyri (Table 1, Figure 3a).

To test for the different mindsets, we focused the analysis on these final decisions and compared these between the different mindsets and the baseline condition. For all of the mindset contrasts we did not observe any activation significant on whole brain level corrected for multiple comparisons. Results of the ROI analysis are reported below.

*Pleasure mindset*

When the participants were instructed to select a portion size if planning to eat with pleasure, increased activity in left OFC was observed (Table 1, Figure 3b). In an adjacent cluster in the OFC, the difference in activity between the pleasure and baseline condition was negatively correlated with the behavioral change in portion size selection (Table S2, Figure S3). The more the participant reduced the selected portion sizes in the pleasure mindset, the stronger the response increase in the respective brain area.

*Healthiness mindset*

Implementing self-control during the healthiness mindset was associated with increased activity in left DLPFC (Table 1, Figure 3c). For this mindset, we also observed a negative behavioral correlation in a nearby cluster. Increased activity difference in left DLPFC was associated with a bigger reduction in portion size selection during the healthiness mindset (Table S2, Figure S3).

*Fullness mindset*

Finally, when the participants were planning to eat to be full until dinner, they showed an increased response in a cluster in left posterior insula (Table 1, Figure 3d).

- Insert Figure 3 and Table 1 here -

*Parametric modulation*

Main effects for the parametric modulation of the attributes expected satiation, healthiness and tastiness across all mindsets are reported in Figure S4 and Table S3. As expected, ROI analysis revealed a positive association between tastiness ratings of the meals and activity in the vmPFC. Furthermore, whole-brain analysis revealed increased activity in posterior visual and parietal areas for meals with low expected satiation and increased activity in lower visual areas for foods that were rated healthier. Planned contrasts between mindsets did not reveal increased parametric modulation of the behavioral ratings in the associated mindsets in vmPFC.

## 4. Discussion

When we make decisions about food, different attributes like tastiness or healthiness have to be integrated to select an action. In the current study, we showed that not only choices between food items, but also portion size selection during pre-meal planning was dependent on the mindset of the individual at the time of choice, which was associated with specific neural processes. For the investigated mindsets fullness, pleasure and healthiness, we observed increased activity in insula, OFC and DLPFC, respectively. We further observed that, although expected satiation was an important predictor for selected portion sizes, in consideration of individual variability and mindset condition also tastiness and healthiness ratings had a significant impact on portion size selection. Finally, we report indications that the mindset effects might be gender specific.

On the behavioral level, we replicated the finding of Brunstrom and Rogers (2009). For the group average, expected satiation was related to the energy density of a food and it was a strong predictor of portion size selection, whereas tastiness and healthiness ratings were not. To better account for inter-individual variability, we investigated the influence of expected satiation, tastiness and healthiness ratings on portion size selection in the different mindsets (baseline, fullness, pleasure, healthiness) using multilevel linear modeling. Expected satiation was again a strong predictor for meal size selection in all four conditions. However, now also tastiness ratings showed a significant contribution to portion size selection. Healthiness ratings only showed an effect in the healthiness mindset. These results confirmed that during pre-meal planning, different attributes of the foods were integrated to form a decision. That this integration might be dependent on the focus during time of choice was further supported by the observed changes in portion size selection during the different mindsets.

Individual energy requirements and energy intakes vary with body size. Consequently, we observed that taller/heavier men selected larger portion sizes than smaller women in the baseline and fullness condition. Satiation signals arise from multiple sites in the gastro-intestinal system to prevent overconsumption during individual meals and thus, to achieve efficient nutrient digestion and absorption (Woods 1991; Cummings et al. 2007). Although one of the key satiation mechanisms is gastric distension, meal sizes are usually considerably smaller than the maximal gastric capacity (Cummings et al. 2007). Consequently, participants chose to select significantly smaller portion sizes during natural decisions in the baseline condition than they could imagine to eat when the time until the next meal was fixed to dinner time as in the fullness condition. Thus, when expecting freedom to choose the time interval until the next meal, it seemed that participants chose to be comfortably satiated rather than to eat as much as possible. Furthermore, during baseline decisions they might have considered additional factors like palatability and chose to eat meals that are less liked in smaller portion sizes, whereas in the fullness condition the main goal was to be full for a long time. This was supported by the observation that tastiness ratings had a seemingly reduced influence on portion size selection in the fullness mindset.

From a neural perspective, eating to be full until dinner was associated with increased activity in left posterior insula. The insula is a key area for the integration of various internal (interoceptive) and external (exteroceptive) stimuli. In particular, more posterior regions process somatic and visceral sensations of the body (Craig 2003; Avery et al. 2017), which suggests a role in the perception of fullness (produced by gastric distention). Activity in posterior insula has been reported to be increased during satiation in response to food images (Thomas et al. 2015) and during gastric distention without food intake (Wang et al. 2008). Therefore, we suggest that the increased activity in left posterior insula was related to interoceptive processes. Participants might have tried to estimate their ideal portion size to reach long-term satiety without overstraining their gastric distention capability. Interestingly, in response to food images, obese in comparison to lean participants showed decreased activity in the insular cortex in a recent meta-analysis (Brooks et al. 2013). Thus, reduced interoceptive awareness of the bodily states might play an important role in obesity by enabling the selection of larger portion sizes.

During the healthiness mindset, participants selected significantly smaller portion sizes in comparison to the baseline condition. In addition, portion size selection was associated with the healthiness rating of a food. This suggests that participants were considering the health aspects of foods more strongly and trying to adjust their meal sizes accordingly. In other words, they were choosing an option that reduces immediate reward outcome in favor of more advantageous long-term consequences. This ability is referred to as self-control and has been reported previously to be important for making healthy food choices and to be negatively associated with body weight (Gunstad et al. 2007; Weller et al. 2008). A crucial brain area for the implementation of cognitive control in general is the prefrontal cortex (Miller et al. 2001; Jurado et al. 2007) with the DLPFC being particularly important for exerting self-control (Hare et al. 2009; Hollmann et al. 2012; Spetter et al. 2017). Importantly, disruptions of the activity in left DLPFC by repetitive transcranial magnetic stimulation during intertemporal choice leads to increased choices of immediate rewards over larger delayed ones (Figner et al. 2010). In agreement with this finding, we observed increased activity in left DLPFC when participants were instructed to particularly consider health aspects, which generally have a delayed impact. Activity in a nearby cluster was directly related to the magnitude of the behavioral change in portion size selection between the healthiness and baseline condition across participants. These results suggest that increased self-control reflected in increased left DLPFC activity led to the selection of smaller portion sizes.

Finally, participants also selected significantly smaller portion sizes when they were planning to eat with pleasure in comparison to free choice. For a comprehensive evaluation of this effect, it must be noted that our mindset effects are always in comparison to the baseline behavior of the individual. The baseline condition is not mindset free, but is dependent on the general eating behavior of the participants. Thus, a reduction in the portion size might be specific to our normal-weight study population and might actually be in the opposite direction in a dieting overweight population, whose eating behavior is characterized by trying to restrict their food intake. Interestingly, mostly men showed a reduction in portion size, whereas most women showed a small increase. We also observed a gender specific effect for the healthiness mindset, men showed a stronger reduction in portion size than women. Several studies report that women are generally more concerned with weight control and health aspects during their food decisions (Wardle et al. 2004; Westenhoefer 2005). Our results might suggest that women making baseline decisions already put more weight on pleasure and health aspects, and restricted their food intake, whereas young men prioritized satiation.

When making decisions for pleasure, one would assume increased processing in brain areas associated with the processing of the pleasurable aspects of eating. As expected, we observed increased activity in left OFC during the pleasure mindset compared with baseline decisions. In several studies it was shown that activations in OFC, close to the observed cluster in our study, were correlated with the subjective pleasantness of food and decreased to a particular food when it was eaten to satiety (sensory-specific satiety) (Small et al. 2001; Gottfried et al. 2003; Kringelbach et al. 2003; Grabenhorst et al. 2010). Finally, in our study, changes in activity in left OFC were associated with the behavioral changes in portion size selection between the pleasure mindset and baseline condition across participants. Indicating that an increased processing of aspects associated with pleasure was related to a stronger decrease in selected portion size.

Changes in behavior that were associated with activity changes in specific brain regions indicated that the focus of attention during the time of choice might indeed be important for stimulus attribute integration and option selection during pre-meal planning. From a neural perspective, a key role in the computation of reward values across different modalities by integrating different attributes to guide the decision is assigned to the vmPFC (Bartra et al. 2013; Clithero et al. 2014). Activity in vmPFC has been shown to be modulated by attributes such as tastiness during choices between snack foods, and has also been reported to be sensitive to mindset induced changes in attribute integration (Hare et al. 2009; Hare et al. 2011a). In our study, we also observed positive parametric modulation of vmPFC activity by behavioral tastiness ratings across all mindsets, but not by healthiness and expected satiation ratings. In addition, we did not observe mindset induced changes in the parametric modulation of vmPFC activity by the respective behavioral ratings. In detail, there was no significantly increased positive parametric modulation in vmPFC in comparison to the other mindsets in the healthiness mindset by healthiness ratings, in the pleasure mindset by tastiness ratings, nor in the fullness mindset by expected satiation ratings. In contrast, Hare et al. (2011a) reported an increased responsiveness of the value signals in vmPFC to healthiness ratings during food choices when focusing on their health aspects. This discrepancy may be explained by differences in the decision tasks used. In contrast to a single decision per food item, our task design included sequential decisions. In addition, the nature of our healthiness ratings might play a role. Healthiness ratings were always given for a 500 kcal portion, which was not necessarily the chosen portion size. Considering that healthiness ratings might not be independent of the portion size that they are given for, their representation at the time of choice might also be dependent on the selected portion size.

Decision making processes in general do not end with the selection of an option. Rather, choices also have to be implemented by activating the necessary motor response and then taking an action. Thus, the computed stimulus values have to be compared to make a choice, which has to be transmitted to the motor system. It has been suggested that the medial PFC/ACC plays an important role in this action-stimulus association (Rudebeck et al. 2008; Hare et al. 2011b); for review: Rushworth et al. (2011);Zald (2009)). This hypothesis is supported by the described anatomical connections of the rostral cingulate motor area to primary motor cortex, several premotor areas and to the ventral horn of the spinal cord (Van Hoesen et al. 1993; Morecraft et al. 2009). Among others, ACC is considered to be particularly involved in behavioral change and update (reviews: Alexander et al. (2011); Kolling et al. (2016)). This fits with our results which show increased ACC activity when a change in response is requested for the final selection of a portion size in comparison to portion size increases or decreases. Increased activity in left motor and somatosensory cortices were probably also related to the implementation of the changed motor response as participants responded with their right hand. The final selection is, however, also the last response in a number of preceding responses. Theoretically, increased activity in motor response related areas for this contrast could also be explained by the summation of activity over multiple responses. Although, the inclusion of variable interstimulus intervals in the task, argue against this possibility.

Finally, as our primary interest of this study was to compare decisions between mindsets, it might seem a disadvantage that mindsets were not completely randomized. Always executing the baseline condition first resulted in an order effect as indicated by slower reaction times in this condition. However, as we did not want the baseline decisions to be influenced by the mindset instructions, we had to accept this fixed order as an inherent part of our study design. As we observed expected mindset specific changes in brain activity, we assume that our results are not due to an order effect. In addition, it is the case that our study design has limited power to decipher whether the observed effects, in particular related to gender, are due to baseline differences or due to differences in their susceptibility to the mindset inductions. The main purpose of this study was to evaluate the general feasibility of inducing mindsets in pre-meal planning and associated consequences on portion size selection. Investigation of larger cohorts in future studies that also include overweight and obese people will contribute additional information to the understanding of pre-meal planning.

To sum up, we provide evidence that not only choices between food items, but also portion size selection during pre-meal planning is dependent on the mindset of the individual at the time of choice. Changing the focus during pre-meal planning was associated with activity changes in mindset specific brain areas and changes in attribute integration resulting in an increase or decrease of selected portion sizes. Given the observed influence of attentional focus on meal size selection, the *per se* cognitive process of pre-meal planning would appear to provide a key opportunity to influence the control of portion size selection by mindset manipulation.

## 5. Conflict of interest

The authors declare no conflict of interest.

## 6. Funding

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**Table 1** Clusters of significant activations for final portion size selection and mindsets

| **Brain Region** | **Side** | **Coordinates** x | y | z | **Cluster size (in voxels)** | **Z** | **P value (FWE corr.)** |
|---|---|---|---|---|---|---|---|
| **Final selection of Portion Size** | | | | | | | |
| Precentral gyrus | L | -18 | -10 | 59 | 160 | 4.32 | 0.001 |
| Anterior cingulate cortex | R | 9 | 32 | 23 | 74 | 4.07 | 0.032 |
| Postcentral gyrus | L | -33 | -34 | 50 | 84 | 3.99 | 0.020 |
| **Healthiness Mindset** | | | | | | | |
| Inferior frontal gyrus | L | -51 | 20 | 23 | 26 | 4.14 | 0.002* |
| **Pleasure Mindset** | | | | | | | |
| Inferior orbital frontal gyrus | L | - 30 | 29 | -16 | 5 | 4.31 | 0.005* |
| **Fullness Mindset** | | | | | | | |
| Insula | L | -33 | -16 | 17 | 2 | 3.81 | 0.035* |

*Region of interest analysis

## Figure captions

**Figure 1** Illustration of the fMRI task in which participants had to select portion sizes which they wanted to consume for lunch for different meals.

**Figure 2** Size of selected portion size in kcal as a function of the different experimental manipulations. Shown is the mean (averaged over meals and participants) with standard error. Comparison against the baseline condition revealed significant mindset effects in portion size selection; *$p<0.01$, **$p<0.001$.

**Figure 3** Brain areas associated with the final selection of a portion size and mindset induced changes in brain activity in comparison to baseline. (a) Shown are significant clusters with increased activity for the final decision to select a portion size in comparison to pre decisions to increase or decrease a portion size combined for all conditions; $p<0.05$ FWE corrected. (b) Selecting a portion size if eating with pleasure was associated with an increased response in left OFC, (c) if eating in consideration of health consequences with left DLPFC and (d) if eating to be full until dinner with left insula. (a: $p<0.05$ FWE corrected, b,c,d: a moderate threshold of $p<0.001$ uncorrected was chosen for display).

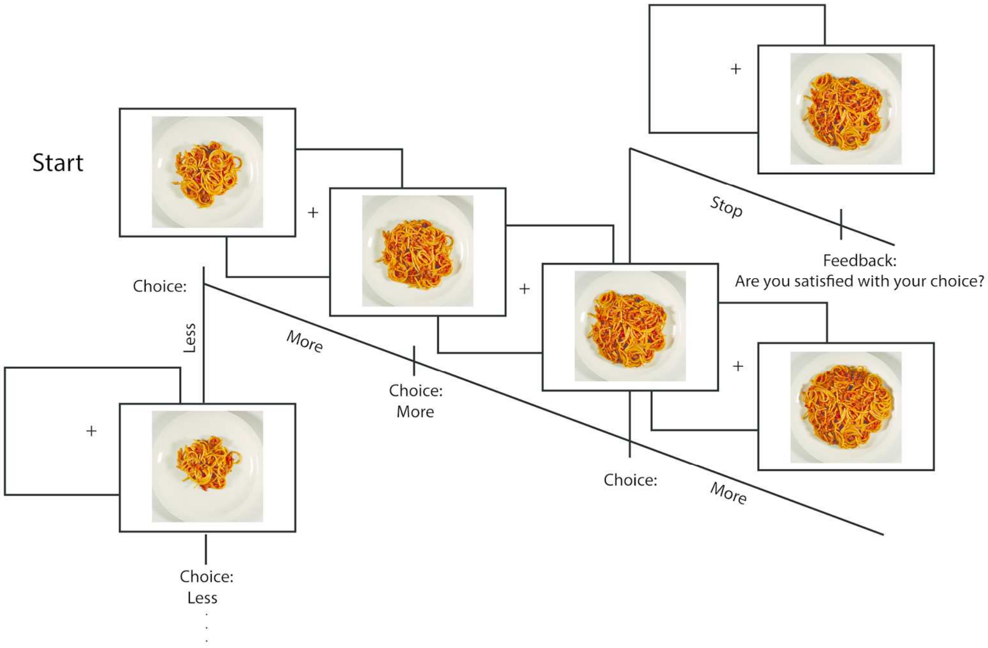

Figure 1 Illustration of the fMRI task in which participants had to select portion sizes which they wanted to consume for lunch for different meals.

178x116mm (300 x 300 DPI)

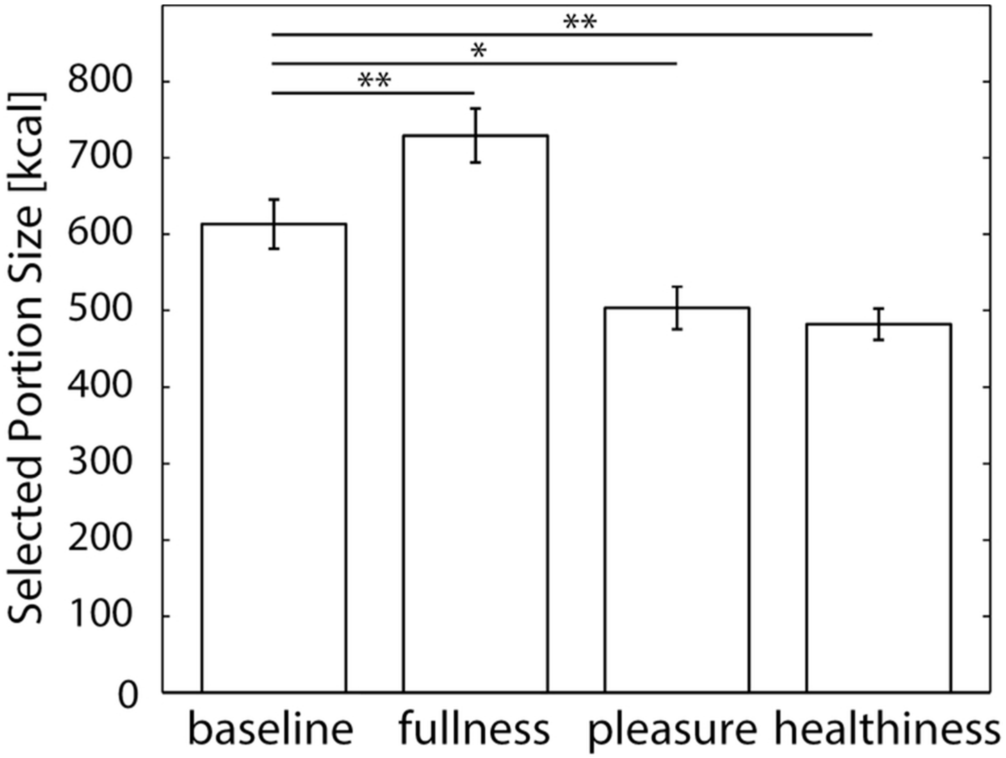

Figure 2 Size of selected portion size in kcal as a function of the different experimental manipulations. Shown is the mean (averaged over meals and participants) with standard error. Comparison against the baseline condition revealed significant mindset effects in portion size selection; *p<0.01, **p<0.001.

64x48mm (300 x 300 DPI)

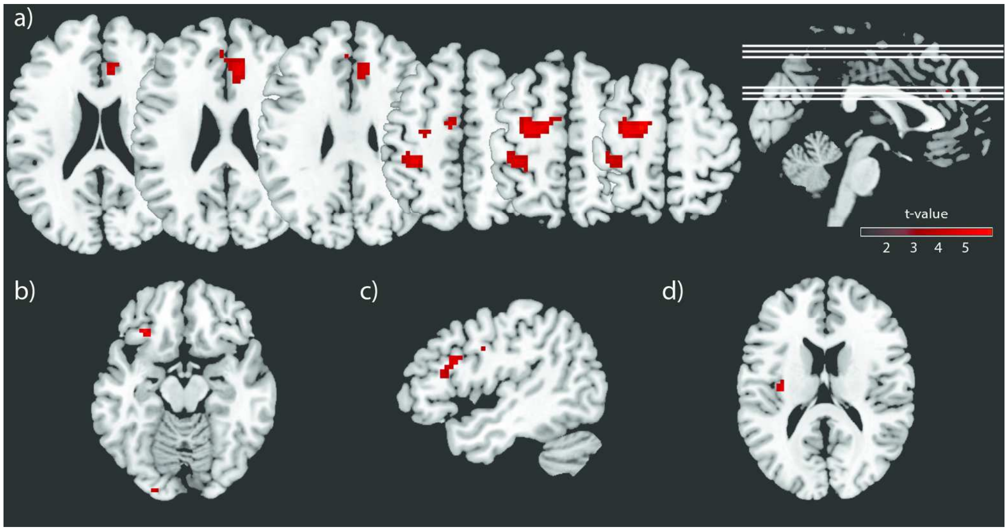

Figure 3 Brain areas associated with the final selection of a portion size and mindset induced changes in brain activity in comparison to baseline. (a) Shown are significant clusters with in-creased activity for the final decision to select a portion size in comparison to pre decisions to increase or decrease a portion size combined for all conditions; $p<0.05$ FWE corrected. (b) Selecting a portion size if eating with pleasure was associated with an increased response in left OFC, (c) if eating in consideration of health consequences with left DLPFC and (d) if eating to be full until dinner with left insula. (a: $p<0.05$ FWE corrected, b,c,d: a moderate threshold of $p<0.001$ uncorrected was chosen for display).

180x94mm (300 x 300 DPI)

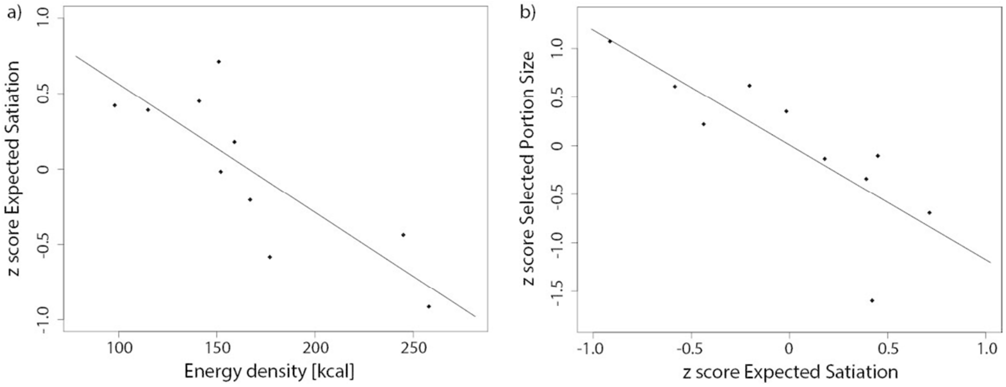

Figure S1 Expected satiation correlates with a) energy density and b) selected portion size of a meal during the baseline condition.

425x162mm (72 x 72 DPI)

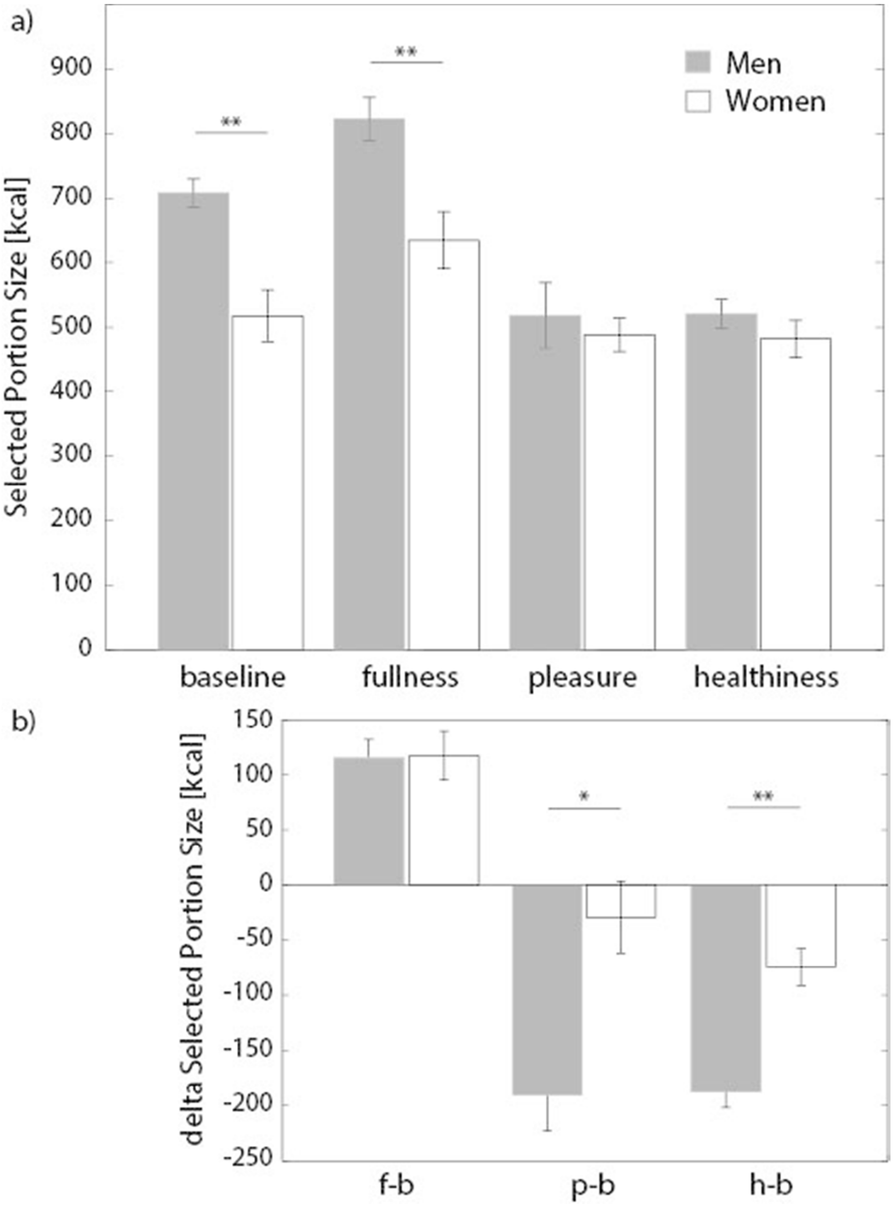

Figure S2 Gender effect in portion size selection with a) showing selected portion sizes during the mindsets and b) showing differences in selected portion sizes between the mindsets and the baseline condition. Displayed is the mean (averaged over meals and participants) with standard error; *p<0.05, **p<0.01.

183x248mm (72 x 72 DPI)

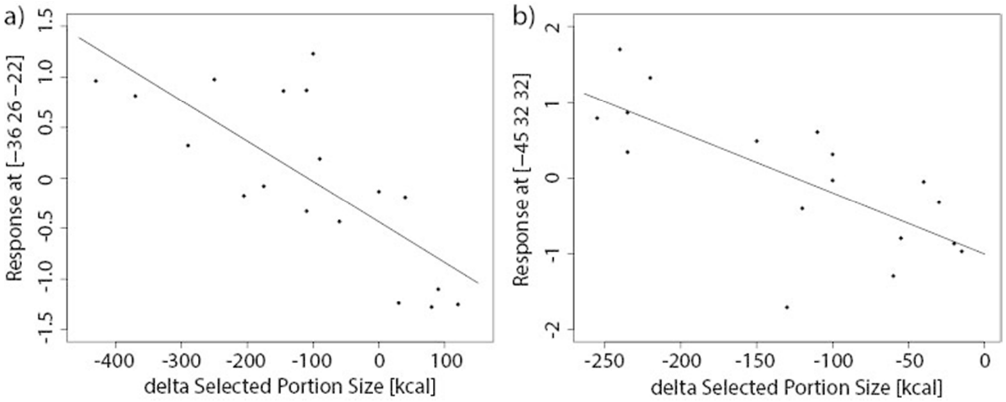

Figure S3 Mindset induced changes in brain activity were associated with behavioral changes in portion size selection in a) the left orbitofrontal cortex for the pleasure mindset and b) the left dorsolateral prefrontal cortex for the healthiness mindset.

274x109mm (72 x 72 DPI)

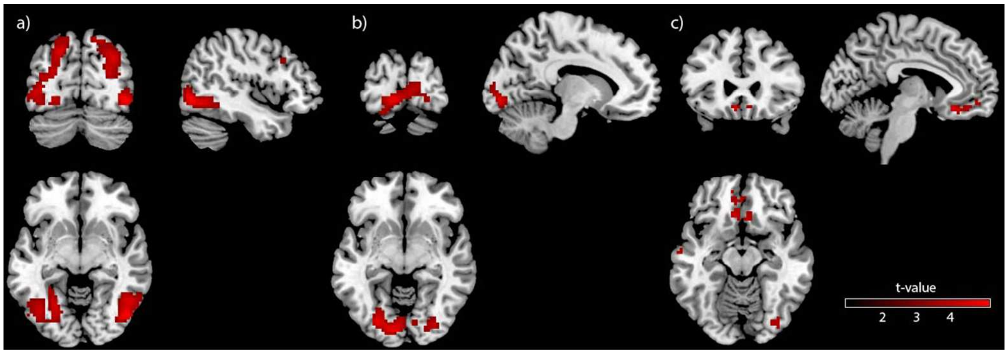

Figure S4 Parametric modulations with behavioral ratings during the final selection of a portion size over all mindsets. (a) Expected satiation was negatively associated with activity in visual and parietal areas, (b) healthiness ratings were positively associated with activity in visual areas and (c) pleasure ratings were positively associated with activity in ventromedial prefrontal cortex. (a moderate threshold of p<0.001 uncorrected was chosen for display).

455x157mm (72 x 72 DPI)

**Table S1** Type and energy density of the ten meals used in the task

| **Food type** | **Energy density [kcal/100g]** |
|---|---|
| Spaghetti bolognese | 141 |
| Meatballs and paprica potatoes | 115 |
| Beef stew with dumplings | 167 |
| Fish and chips with peas | 177 |
| Macaroni with cheese | 151 |
| Spinach and ricotta tortellini with tomato sauce | 152 |
| Quiche Lorraine and salad | 258 |
| Penne and pesto | 245 |
| Sweet and sour chicken with egg fried rice | 159 |
| Salad with chicken, parmesan and croutons | 98 |

**Table S2** Clusters showing significant correlations with behavioral changes in portion size selection for different mindsets in comparison to baseline

| Brain Region | Side | Coordinates | | | Cluster size (in voxels) | Z | P value (uncorr.) |
|---|---|---|---|---|---|---|---|
| | | x | y | z | | | |
| **Healthiness Mindset** | | | | | | | |
| Middle/Inferior frontal gyrus | L | -45 | 32 | 32 | 6 | 3.50 | <0.001 |
| **Pleasure Mindset** | | | | | | | |
| Inferior orbital frontal gyrus | L | -36 | 26 | -22 | 6 | 3.60 | <0.001 |

**Table S3** Clusters showing significant parametric modulations with behavioral ratings during the final selection of a portion size

| Brain Region | Side | Coordinates x | Coordinates y | Coordinates z | Cluster size (in voxels) | Z | P value (FWE corr.) |
|---|---|---|---|---|---|---|---|
| **Expected satiation rating** | | | | | | | |
| Inferior temporal gyrus | R | 45 | -73 | -7 | 286 | 4.81 | <0.001 |
| Middle occipital gyrus | L | -24 | -79 | 20 | 996 | 4.61 | <0.001 |
| Superior parietal lobule | R | 18 | -64 | 56 | 740 | 4.60 | <0.001 |
| **Tastiness Rating** | | | | | | | |
| Medial orbitofrontal gyrus | L | -6 | 26 | -13 | 6 | 3.84 | 0.019* |
| **Healthiness Rating** | | | | | | | |
| Lingual gyrus | L | -12 | -88 | -7 | 507 | 4.43 | <0.001 |

*ROI analysis