



Supersize my brain: A cross-sectional voxel-based morphometry study on the association between self-reported dietary restraint and regional grey matter volumes

Laura N. van der Laan^{a,*}, Lisette Charbonnier^a, Sanne Griffioen-Roose^b, Floor M. Kroese^c, Inge van Rijn^b, Paul A.M. Smeets^{a,b}

^a Image Sciences Institute, University Medical Center Utrecht, Postal address: Heidelberglaan 100 Q02.4.45, 3584CX Utrecht, The Netherlands

^b Division of Human Nutrition, Wageningen University and Research centre, Postal address: PO box 8129, bode 62, 6700 EV Wageningen, The Netherlands

^c Department of Clinical and Health Psychology, Utrecht University, Postal address: Padualaan 14, 3584CH Utrecht, The Netherlands

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ABSTRACT

Restrained eaters do not eat less than their unrestrained counterparts. Proposed underlying mechanisms are that restrained eaters are more reward sensitive and that they have worse inhibitory control. Although fMRI studies assessed these mechanisms, it is unknown how brain anatomy relates to dietary restraint. Voxel-based morphometry was performed on anatomical scans from 155 normal-weight females to investigate how regional grey matter volume correlates with restraint. A positive correlation was found in several areas, including the parahippocampal gyrus, hippocampus, striatum and the amygdala (bilaterally, $p < 0.05$, corrected). A negative correlation was found in several areas, including the inferior frontal gyrus, superior frontal gyrus, supplementary motor area, middle cingulate cortex and precentral gyrus ($p < 0.05$, corrected). That higher restraint relates to higher grey matter volume in reward-related areas and lower grey matter volume in regions involved in inhibition, provides a neuroanatomical underpinning of theories relating restraint to increased reward sensitivity and reduced inhibitory capacity.

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1. Introduction

Dietary restraint refers to the intentional and sustained restriction of food intake for the purposes of weight-loss or weight-maintenance (Herman & Mack, 1975a). However, in contrast to this formal definition of restrained eating there is ample evidence that self-reported restrained eaters, that is, people who score high on self-report scales of dietary restraint, do not eat less than their unrestrained counterparts (de Witt Huberts, Evers, & De Ridder, 2013; Stice, Fisher, & Lowe, 2004; Stice, Cooper, Schoeller, Tappe, & Lowe, 2007; Stice, Sysko, Roberto, & Allison, 2010). In fact, Herman & Mack (1975a) established in the seventies already that self-reported restrained eaters over- rather than under-consume. They also were the first to demonstrate that self-reported restrained eaters break their pattern of food restriction after receiving a preload of food. Many studies have replicated this preload-induced loss of dietary control, often denoted as ‘disinhibition effect’ since then, although null findings have also emerged

(Knight & Boland, 1989; Lowe, 1993; Polivy, Heatherton, & Herman, 1988; Van Strien, 2000). Furthermore, self-reported restrained eaters are more likely to be overweight (Klesges, Isbell, & Klesges, 1992; Laessle, Tuschl, Kotthaus, & Pirke, 1989) and healthy weight self-reported restrained eaters/dieters might even be at increased risk for weight gain and future onset of binge-eating (French, Jeffery, & Wing, 1994; Klesges et al., 1992; Mann et al., 2007; Stice, Presnell, Shaw, & Rohde, 2004; Tanofsky-Kraff et al., 2006; Lowe, Doshi, Katterman, & Feig, 2013).

The evidence outlined above suggests that the self-reported status of being a restrained eater is a marker for someone's intention rather than actual success in restricting food intake. It appears that healthy weight self-reported restrained eaters mainly diet to avoid weight gain instead of to lose weight (Chernyak & Lowe, 2010). Thus, self-reports of restraint in healthy weight individuals might rather signify perceived difficulties in maintaining current weight and dealing appropriately with everyday food temptations than their actual behavior (Lowe & Levine, 2005; de Ridder, Adriaanse, Evers, & Verkes, 2014). Explanations for the divergence between self-reported restrained eaters' intention and behavior has been sought in two possible directions, namely that individuals high in self-reported restraint might have a reduced inhibitory con-

* Corresponding author.

E-mail address: nynke@isi.uu.nl (L.N. van der Laan).

control capacity, or an increased sensitivity to food reward (or both) (e.g., Nederkoorn, Van Eijs, & Jansen, 2004; Papiés, Stroebe, & Aarts, 2007). Although it has repeatedly been shown that people high in self-reported dietary restraint are worse at inhibition (Houben & Jansen, 2014; Nederkoorn et al., 2004), at least one other study found the opposite, namely that self-reported restrained eaters were better at inhibiting responses to food cues in a computer task than self-reported unrestrained eaters (Meule, Lukito, Voegelé, & Kubler, 2011). More univocal support exists for the second proposition, that self-reported restrained eaters have an increased sensitivity to food rewards: individuals high (versus low) in self-reported restraint show greater salivary response to the sight and smell of food (Brunstrom, Yates, & Witcomb, 2004; Klajner, Herman, Polivy, & Chhabra, 1981; LeGoff & Spigelman, 1987), they report having stronger cravings for palatable foods (Gendall, Joyce, Sullivan, & Bulik, 1998; Polivy, Coleman, & Herman, 2005), they have a stronger implicit preference for palatable foods (Houben, Roefs, & Jansen, 2010; Houben, Roefs, & Jansen, 2012), are more likely to overeat in response to the smell, sight or thoughts of palatable food (Fedoroff, Polivy, & Herman, 2003; Fedoroff, Polivy, & Herman, 1997; Papiés & Hamstra, 2010), and they have an attentional bias towards palatable energy-rich foods (Forestell, Lau, Gyurovski, Dickter, & Haque, 2012), especially when pre-exposed to palatable food cues (Papiés, Stroebe, & Aarts, 2008), although null findings have also appeared (e.g., Werthmann et al., 2013).

Functional neuroimaging studies suggest that restrained eaters' behaviorally apparent increased reward response to foods is also reflected in an increased responsiveness of their brain's reward circuitry during both viewing and tasting food (Burger & Stice, 2011; Coletta et al., 2009; Demos, Kelley, & Heatherton, 2011; Wagner, Boswell, Kelley, & Heatherton, 2012): Burger and Stice (2011) found that participants who were higher in self-reported dietary restraint had stronger activation in the right orbitofrontal cortex (OFC) in response to tasting a milkshake. Coletta et al. (2009) showed that the normal drop in rewarding value of food after eating was not observed in self-reported restrained eaters. Instead, when self-reported restrained eaters were sated (compared to hungry) they had stronger activation in brain areas involved in hunger and reward (OFC, insula) in response to food pictures (Coletta et al., 2009). Furthermore, when women high in self-reported restraint consumed a milkshake as preload (compared to water) they showed greater activation in the dorsal striatum in response to pictures of appetizing foods (Demos et al., 2011). Combined, these results suggest that restrained eaters have an increased response in reward related brain regions upon viewing and tasting food, particularly when they are in a sated state.

Although the evidence outlined above suggests that self-reported restrained eaters have altered functional brain responses to food, less is known about the role of more stable – anatomical – brain characteristics in restrained eating, such as regional grey matter volume. Regional differences in grey matter volume can provide valuable information about normal and abnormal neuroanatomy, and have been linked to individual differences in general personality traits (DeYoung et al., 2010). It is generally thought that a greater volume of a specific brain structure may signify greater power to carry out specific functions associated with that structure (DeYoung et al., 2010).

To our knowledge, only one earlier study investigated the relation between dietary restraint and regional grey matter volume (Brooks et al., 2011). This study was primarily set up to investigate grey matter volume in two subtypes of anorexia patients and reported no significant relation between dietary restraint scores and regional brain volumes in their healthy control group. However, because variations in brain structure associated with personality characteristics in the healthy range are relatively small, their null-finding might be explained by the low number of healthy

control subjects (n=21). Studies on the structural basis of personality characteristics usually include much higher numbers of participants (i.e., 100 subjects or more: DeYoung et al., 2010; Fuentes et al., 2012). In the present study, we aimed to investigate how regional brain volume covaries with level of self-reported dietary restraint in a large population of normal weight females. Investigating this is relevant because it yields insights into the brain characteristics of a population at risk for developing problematic eating behaviors and becoming overweight.

Building on the findings from functional neuroscience studies described above, we hypothesized that regional grey matter volume in brain regions involved in food reward and inhibitory control correlate with level of dietary restraint.

Relating food-related and personality related concepts to anatomical features of the brain can potentially reveal common underlying components and any neural substrates. Such an approach may provide new insights into how eating behavior and different cognitive functions are related to each other and which regions underlie those functions. By identifying the brain regions where grey matter volume covaries with personality or eating behavior, we can build brain-based theories of personality and eating behavior. Knowing how brain differences relate to the expression of different traits and behaviors opens directions for future research in both brain structure and eating behavior.

2. Materials and methods

2.1. Ethics statement

Data used for the analyses in this article was taken from studies that were approved by the Medical Ethical Committee of either the University Medical Center Utrecht or of Wageningen University. All subjects provided written informed consent.

2.2. Participants

The sample consisted of 155 females with a healthy weight (mean age \pm SD: 22.9 \pm 4.0, range: 18–40; mean Body Mass Index (BMI) \pm SD: 21.5 \pm 1.7, range: 18.1–25.2), who participated in seven earlier unrelated studies in our and affiliated labs (six published studies (Charbonnier, van der Laan, Viergever, & Smeets, 2015; Griffioen-Roose et al., 2014; Smeets, Kroese, Evers, & De Ridder, 2013; van der Laan, De Ridder, Viergever, & Smeets, 2012; van Rijn, de Graaf, & Smeets, 2015) and one study in preparation). Self-reported length and height (to calculate BMI) were acquired during the screening phase of the study they participated in. Participant selection for the current study was limited to young adult women because they generally score higher on restraint and because of known gender differences as well in reasons for dieting as in brain anatomy and function (Cahill, 2006; Luders, Gaser, Narr, & Toga, 2009; Neumark-Sztainer, Sherwood, French, & Jeffery, 1999; Pingitore, Spring, & Garfield, 1997). All participants were right-handed, non-smokers and had a stable weight (did not gain or lose >5 kg in the past 6 months). All participants were healthy, i.e., they reported having no eating disorder and no neurological, metabolic, endocrine or gastrointestinal disorders. Furthermore, none of the participants had a food allergy or followed a medically prescribed diet. Participants were recruited with posters and flyers at the University Medical Center Utrecht or at Wageningen University and Research centre in The Netherlands.

2.3. Dietary restraint measurement

The restrained eating scale of the Dutch Eating Behavior Questionnaire (Van Strien, Frijters, Bergers, & Defares, 1986) was used

to assess participants' level of dietary restraint. This scale consists of ten items, for example, "Do you deliberately eat less in order not to become heavier?" The items have a six options format with 1 = never, 2 = rarely, 3 = sometimes, 4 = often, 5 = usually and 6 = always. Scores on the ten items were averaged, resulting in a restraint score for each participant. The mean level of dietary restraint in our sample was 2.46 (SD = 0.62), which is in the 'below average' range for non-obese females, according to the norm tables of the DEBQ (Van Strien et al., 1986). Restraint scores were normally distributed (Shapiro-Wilk statistic = 0.98, $p > 0.05$). The restraint scale had a good internal consistency in our study sample (Cronbach's $\alpha = 0.87$). For all participants, this questionnaire was administered during the screening phase of the study they participated in.

2.4. Anatomical MRI acquisition

Data (T_1 -weighted anatomical scans) from two scan sites were used in this study. For 104 participants, MRI scanning was performed on a 3T Philips Achieva MRI scanner (Philips Healthcare, Best, The Netherlands), with a 3D gradient echo sequence (TR = 8.4 ms, TE = 3.8 ms, flip angle 8° , FOV = 288 mm \times 288 mm \times 175 mm, 175 sagittal slices, voxel size = 1 \times 1 \times 1 mm, total scan duration = 284 s). For the other 51 participants, MRI scanning was performed on a 3T Siemens Magnetom Verio MRI scanner (Siemens, Erlangen, Germany) with an MPRAGE sequence (TR = 1900 ms, TE = 2.26 ms, flip angle 9° , FOV = 256 mm \times 256 mm \times 192 mm, 192 sagittal slices, voxel size = 1 \times 1 \times 1 mm, total scan duration = 349 s).

2.5. Voxel-based morphometry (VBM) processing

Structural MRI data were processed and analyzed using the SPM8 software package (Wellcome Department of Imaging Neuroscience, London, United Kingdom) ran with MATLAB R2013A (The Mathworks Inc, Natick, MA). The processing steps were largely based on the suggestions made by Ashburner (2010), which we will summarize below. The T_1 -weighted scans were segmented into tissue class images of grey matter, white matter, cerebrospinal fluid (CSF), skull, soft tissue outside of the brain, and air outside of the head, with the use of the 'new segment' routine. The DARTEL toolbox (Ashburner, 2007) was used to increase the accuracy of inter-subject alignment by modelling the shape of each brain using millions of parameters (3 parameters for each voxel). The DARTEL routine in SPM creates a population average template (DARTEL template space) by the following procedure: first, the average of all the GM and WM tissue class images is calculated to create an initial template. Subsequently, the deformations from this template to the individual tissue class images were computed, and inverses of these deformations were applied to regenerate a new template. This was repeated 6 times, resulting in a final, most accurate (Ashburner, 2010), population average template (in DARTEL template space) which is used in the following steps. In addition to the template, this step also results in a flow field for each subject, which provides information about how each individual grey matter tissue class image should be deformed to fit the population average (DARTEL template space). Next, all images are normalized to MNI space. First, an affine transformation was calculated which maps the population average (DARTEL template space) to MNI space. Subsequently, by using this calculation (DARTEL template space to MNI space) as well as the flow fields from the previous step (participant space to DARTEL template space) all grey matter tissue class images were brought to MNI space. In this step, the spatially normalized segmentations of grey matter were also modulated with the Jacobian determinants from the transformation, in order to adjust for the volume changes resulting from the transformation. Finally, images

were smoothed with a 3-D Gaussian filter of 8 mm full width at half maximum.

2.6. Statistical analysis

To investigate how regional grey matter volumes correlate with restraint scores, we entered all 155 smoothed grey matter tissue maps into a multiple regression analysis in SPM with age, BMI, scanner site, and restraint score as covariates. Age and BMI were included to control for possible confounding effects and nuisance (Hu et al., 2011; Taki et al., 2008; Veit et al., 2014). Scanner site was included to control for scanner effects (Stonnington et al., 2008). The intercept was modeled as well. Analyses were corrected for total intracranial volume by global normalization with proportional scaling. Total intracranial volume was obtained by summing up the overall volumes of grey matter, white matter and CSF for each participant.

A statistical threshold of $p < 0.05$ corrected for multiple comparisons across the whole brain was used. This threshold was implemented by means of cluster size correction in AFNI's 3dClustSim module (the successor of AlphaSim; Cox, 1996). 3dClustSim calculates the minimum size of non-noise clusters at a given uncorrected threshold by performing Monte Carlo simulations (5000 iterations) of random noise with the data's voxel size, the number of voxels in the inclusive mask and the inherent smoothness of the data. These simulations indicated that results surviving a threshold of $p < 0.05$ uncorrected, with a cluster extent of $k \geq 2817$ voxels can be considered significant corrected for multiple comparisons.

3. Results

There was a significant positive association between dietary restraint scores and grey matter volumes in several areas (Fig. 1; Table 1), including bilateral clusters in the supramarginal gyrus, bilateral clusters in the middle frontal gyrus, and clusters in the inferior temporal gyrus, precuneus and the rectus/orbital part of the superior frontal gyrus. Furthermore, there was a significant positive correlation with dietary restraint in bilateral clusters in the limbic system. The cluster in the left hemisphere includes parts of the dorsal striatum (putamen, pallidum), hippocampus, amygdala, and parahippocampal gyrus. The cluster in the right hemisphere includes parts of the right dorsal striatum (putamen), hippocampus, amygdala and parahippocampal gyrus.

There was a significant negative association between dietary restraint scores and grey matter volume in several areas (Fig. 2; Table 2), including a cluster stretching from the middle/anterior cingulate cortex to the supplementary motor area and the precentral gyrus, and clusters in the temporal pole/insula, cerebellum, paracentral lobule, cuneus, postcentral gyrus/inferior frontal gyrus and precentral gyrus.

4. Discussion

Our aim was to investigate how regional brain volumes covary with level of self-reported dietary restraint in normal weight females. In line with our expectations, we found that the degree of self-reported restrained eating was associated positively with regional grey matter volumes in several areas, including areas related to reward-related processing. We found that restraint correlated negatively with regional grey matter volume in several areas, including regions involved in inhibition. Self-reported restraint was correlated positively with a cluster in the orbitofrontal cortex and bilateral clusters in the brain comprising the parahippocampal gyrus, hippocampus, the dorsal striatum (putamen/pallidum) and the amygdala. The orbitofrontal cortex is

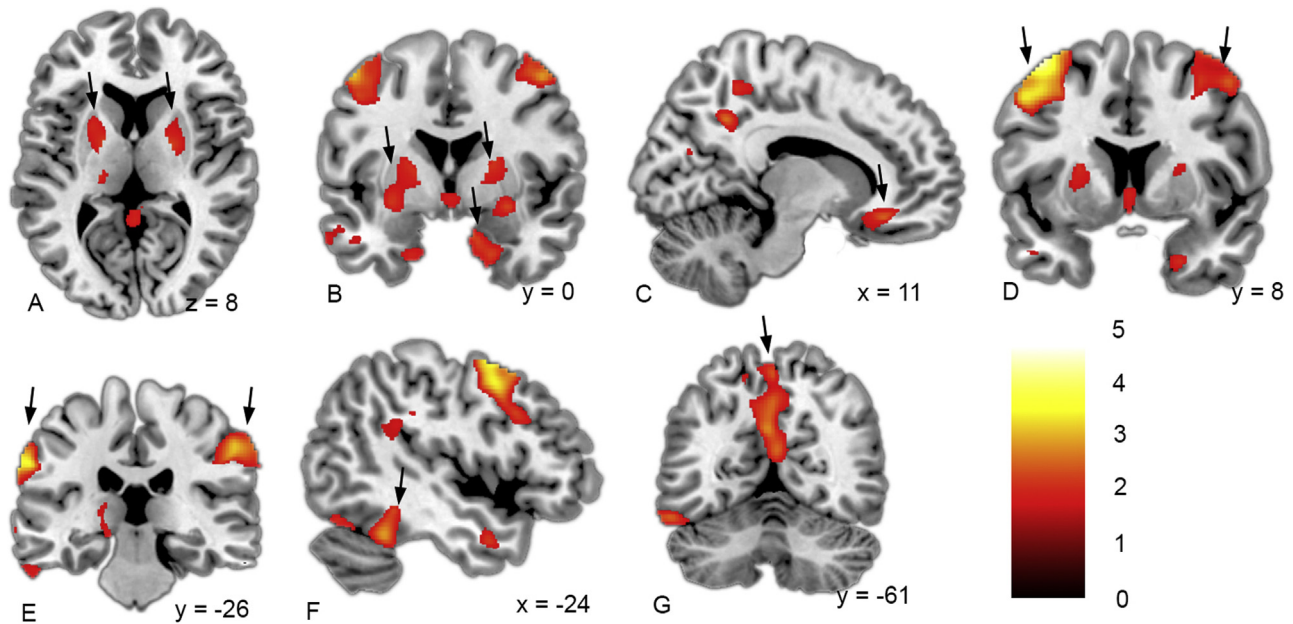


Fig. 1. Brain regions with significant positive associations between grey matter volume and dietary restraint scores. (A, B) Bilateral clusters in putamen/pallidum/amygdala/parahippocampal gyrus; (C) Cluster in rectus/orbitofrontal cortex; (D) bilateral clusters in middle frontal gyrus; (E) bilateral clusters in supramarginal gyrus; (F) cluster in inferior temporal gyrus; (G) cluster in precuneus. VBM results are thresholded at $p < 0.05$ corrected.

Table 1

Brain regions in which regional grey matter volume was significantly¹ positively associated with restraint scores.

Brain region	Side	MNI coordinates			Cluster		
		X	Y	Z	size k	Z	T
Middle frontal gyrus	L	-42	8	60	11031	4.51	4.68
Precentral gyrus/middle frontal gyrus	L	-52	13	43		3.99	4.10
Precentral gyrus	L	-48	2	56		3.63	3.72
Supramarginal gyrus	L	-66	-30	36	5065	4.38	4.53
Supramarginal gyrus	L	-68	-37	26		2.71	2.74
Superior temporal gyrus	L	-58	-37	20		2.17	2.19
Inferior temporal gyrus	L	-51	-43	-25	8410	3.40	3.47
Inferior temporal gyrus	L	-66	-11	-26		3.13	3.19
Inferior temporal gyrus	L	-49	-41	-15		2.87	2.91
Supramarginal gyrus	R	57	-25	42	6717	3.31	3.38
Supramarginal gyrus	R	48	-20	31		3.25	3.31
Inferior parietal lobule	R	51	-35	55		2.23	2.25
Precuneus	L	-4	-58	31	21015	3.16	3.22
Precuneus	R/L	0	-64	59		3.07	3.12
Precuneus/Calcarine gyrus	R	2	-65	21		3.06	3.11
Middle frontal gyrus	R	46	0	55	6377	3.00	3.05
Middle frontal gyrus	R	50	11	49		2.82	2.86
Middle frontal gyrus	R	53	18	42		2.61	2.64
Parahippocampal gyrus	R	12	4	-25	9655	2.86	2.90
Amygdala/hippocampus/putamen/pallidum	R	29	-3	-10		2.79	2.83
Parahippocampal gyrus	R	14	-9	-29		2.76	2.80
Thalamus	L	-16	-9	-31	9655	2.86	2.90
Putamen/amygdala	L	-29	-2	-8		2.37	2.39
Pallidum	L	-17	-3	4		2.32	2.35
Rectus/superior frontal gyrus, orbital part	R	12	32	-13	2025	2.67	2.71
Rectus	R	2	22	0		2.21	2.23
NA	R/L	0	11	-1		2.14	2.15

¹ A combined threshold of $p < 0.05$ uncorrected and $k > 2817$; which equals $p < 0.05$ corrected for multiple comparisons across the whole brain, was employed.

thought to have a role in decision-making and evaluating the value of rewards (Kringelbach, 2005). Functional neuroimaging studies have shown that activation in the orbitofrontal cortex correlates with the value (e.g., pleasantness) of rewarding stimuli (Bartra, McGuire, & Kable, 2013; Kringelbach, O'Doherty, Rolls, & Andrews, 2003). The bilateral clusters in the limbic system are located subcortically and are part of the mesolimbic dopamine circuit which is involved in the motivation to eat and reward/emotion processes in general (Berridge, Ho, Richard, & DiFeliceantonio, 2010). The hip-

pocampus is well-known for its role in generating memories in general (Squire et al., 2010), and memories of certain characteristics of recently eaten foods (Higgs, 2008). The putamen and amygdala are among the regions of the brain that receive the majority of dopamine projections from the midbrain (Riccardi et al., 2006). Earlier studies showed that exposure to food results in increased dopamine levels in the dorsal striatum and that these dopamine levels correlated with the pleasantness of the food (Small, Jones-Gotman, & Dagher, 2003; Volkow et al., 2002, 2003). Moreover,

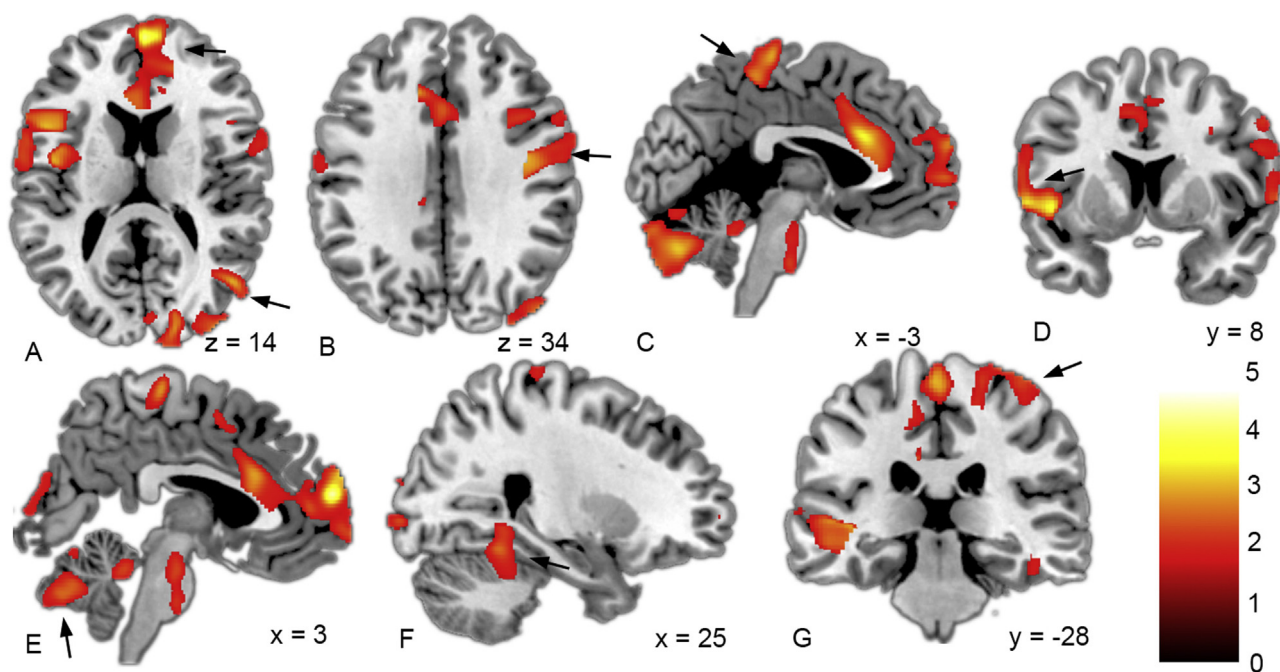


Fig. 2. Brain regions with significant negative associations between grey matter volume and dietary restraint scores. (A) Upper arrow: cluster in medial part of superior frontal gyrus, lower arrow: cluster in middle temporal gyrus; (B) cluster in opercular part of inferior frontal gyrus/postcentral gyrus; (C) cluster in paracentral lobule/supplementary motor area/middle cingulate/precuneus; (D) cluster in superior temporal pole; (E) cluster in cerebellum; (F) cluster in fusiform gyrus/cerebellum; (G) cluster in precentral gyrus. VBM results are thresholded at $p < 0.05$ corrected.

Table 2

Brain regions in which regional grey matter volume was significantly¹ negatively associated with restraint scores.

Brain region	Side	MNI coordinates			Cluster		
		X	Y	Z	size k	Z	T
Superior frontal gyrus, medial part	R	2	61	16	20286	4.48	4.65
Anterior cingulate	L	-1	21	26		3.74	3.83
Superior frontal gyrus, medial part	R	4	66	26		3.26	3.32
Superior temporal pole	L	-57	13	-2	176540	4.08	4.21
Superior temporal pole/insula	L	-46	10	-3		3.82	3.92
Rolandic operculum	L	-46	-3	7		3.75	3.84
Cerebellum	L	-1	-78	-34	25643	3.38	3.45
Middle occipital gyrus	L	-37	-86	2		3.21	3.27
Cerebellum	R	7	-69	-31		2.87	2.91
Paracentral lobule/border supplementary motor area	R/L	0	-26	70	5893	3.26	3.32
Precuneus	L	-2	-36	58		2.93	2.98
Superior parietal lobule	L	-20	-44	76		2.38	2.41
Middle temporal gyrus	R	49	-69	15	12584	3.17	3.23
Cuneus	R	19	-90	12		2.93	2.98
Cuneus	R	10	-103	8		2.91	2.96
Postcentral gyrus/insula	R	40	-10	33	10229	3.06	3.12
Frontal inferior gyrus, opercular part	R	58	15	29		3.10	3.16
Precentral gyrus	R	58	10	40		2.46	2.49
Fusiform gyrus	R	24	-48	-14	7320	2.72	2.76
Cerebellum	R	6	-45	-23		2.64	2.67
Cerebellum	L	-4	-49	-25		2.14	2.16
Precentral gyrus	R	19	-22	64	2828	2.64	2.68
Precentral gyrus	R	38	-26	67		2.47	2.50
Postcentral gyrus	R	29	-30	74		2.46	2.49

¹ A combined threshold of $p < 0.05$ uncorrected and $k > 2817$; which equals $p < 0.05$ corrected for multiple comparisons across the whole brain, was employed.

in their 2003 PET study, Volkow et al. (2003) showed that self-reported dietary restraint was positively correlated with dopamine response to food (smelling and tasting) in the dorsal striatum. This finding is paralleled by a functional MRI study on the neural response to food pictures in restrained women by Demos et al. (2011). When highly restrained women consumed a milkshake as preload they showed greater activation in the left putamen and amygdala when viewing pictures of appetizing foods than when they consumed only water. These neuroimaging findings are in

line with the well-established behavioral findings that women high in self-reported dietary restraint are more sensitive to rewarding food cues in general (Brunstrom et al., 2004; Fedoroff et al., 2003; Houben et al., 2010), and possibly even more after a dietary violation (Herman & Mack, 1975a). Our study extends these behavioral and functional neuroimaging findings by showing that in these same areas, also more stable anatomical features, e.g., grey matter volumes, are related to the degree of restraint. This suggests that self-reported restrained eaters' increased sensitivity to food

reward might be related to increased grey matter volume in these subcortical areas.

We also found correlations between restraint and grey matter volume in areas that are part of the somatosensory association cortex (supramarginal gyrus) and areas of the visual cortex (middle occipital gyrus, calcarine gyrus). In functional neuroimaging it is often observed that increased activation in reward-related areas (e.g., orbitofrontal cortex, ventral striatum) to rewarding stimuli (e.g., viewing pictures of appealing foods) is accompanied with increased activation in areas of the visual system (van der Laan, De Ridder, Viergever, & Smeets, 2011). This co-activation is often interpreted by that rewarding stimuli lead to heightened activation and thereby more extensive visual processing (Killgore & Yurgelun-Todd, 2007).

We found a negative correlation between self-reported dietary restraint and grey matter volume in three areas involved in inhibition, namely the dorsofrontomedial prefrontal cortex (medial part of superior frontal gyrus), the opercular part of the inferior frontal gyrus and a cluster on the border of the supplementary motor area and paracentral lobule, stretching to the middle cingulate cortex. The inferior frontal gyrus is thought to have an important role in tasks that involve response inhibition and the opercular part of the inferior frontal gyrus has previously been shown to activate during response inhibition (Aron, Robbins, & Poldrack, 2014; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Aron et al., 2014). The supplementary motor area is an intermediate link in the pathway from ventral striatum to pre-SMA, SMA to motor cortex, which is involved in the planning and execution of behavior (Haggard, 2008, 2009). The SMA and other areas in this pathway are increasingly being implicated in executive control and inhibition. It has been shown that the (pre-)SMA activates during inhibitory actions to food and nonfood stimuli (Hendrick, Luo, Zhang, & Li, 2012; Hollmann et al., 2012; Ma et al., 2012; Pawliczek et al., 2013; Tuulari et al., 2015). Also, it has been shown that emotional stimuli can influence how the SMA influences excitability of the motor cortex (Oliveri et al., 2003). In a recent study, we found that weight-concerned subjects who are more successful in rejecting high energy snacks had increased activation in the SMA during food choice (van der Laan, De Ridder, Viergever, & Smeets, 2014) which suggests a role of the SMA in food-related self-control. Our findings are also in line with an earlier VBM study which found that a lack of self-control and self-inhibition, as measured by a personality inventory, was related to lower grey matter volume in the SMA (Matsui et al., 2002). The significant cluster stretched from the SMA to the middle cingulate cortex which is functionally connected to the SMA and as well has been implicated to be involved the regulating of approach and avoidance behaviors (Small, Zatorre, Dagher, Evans, & Jones-Gotman, 2001; van Rijn et al., 2015). The medial part of the superior frontal gyrus is functionally connected to the pre-SMA and is thought to exert control over pre-SMA during inhibition of (negative) emotions (Kuhn, Haggard, & Brass, 2014). The lower grey matter volume in the medial part of the superior frontal gyrus, inferior frontal gyrus, SMA and middle cingulate found in the present study might be related to self-reported restrained eaters' reduced inhibitory capacity.

As noted, only one earlier study, by Brooks and colleagues (2011), investigated the relation between dietary restraint and regional grey matter volume. Although their null-finding might be explained by their low number of healthy control subjects ($n = 21$), another difference with our study is the scale used to assess restrained eating. Brooks et al. (2011) used the Eating Disorder Examination-Questionnaire, which has its origins as assessment tool for the presence and severity of eating disorder symptoms. We used the restraint scale of the DEBQ, which has been developed to assess eating behaviors in the general population. The DEBQ is one of the most widely used restraint scales and the factor structure has

been well replicated across different samples (Allison, Kalinsky, & Gorman, 1992; Fox, Page, Peters, Armstrong, & Kirby, 1994; Van Strien et al., 1986). The scale used to measure dietary restraint appears to be of influence: in a study that compared all measures of restraint, it was found that only the Eating Inventory Restraint Scale (Stunkard & Messick, 1985) was predictive of successful long-term (6 months) dietary restriction (Williamson et al., 2007). The DEBQ restraint scale, amongst other widely used scales, such as the Revised Restraint Scale (Herman & Mack, 1975b) and the Current Dieting Questionnaire (Lowe, 2015), did not show a relation with intake. DEBQ Restraint ratings might thus be more indicative of intention and perceived difficulties to resist food temptations than actual ability to restrict intake.

Since cross-sectional VBM studies only provide insight into the brain anatomy at a single point in time, it is unclear whether observed differences are a cause or consequence of dietary restraint. It might be that the observed differences in grey matter volume are predispositional factors in developing restraint. That is, that some people are born with increased grey matter volumes in the areas identified in our study which renders them more sensitive to (food) reward, and thereby increase the perceived difficulty in dealing with everyday food temptations. Although research on the relation between grey matter volumes and future (eating) behavior is scarce, at least one study supports this proposition. Yokum and colleagues (Yokum, Ng, & Stice, 2012) found a trend that reduced grey matter volumes in regions involved in inhibition were related to increases in BMI over 1-year follow up. A second explanation could be that restrained eaters have acquired increased grey matter volume in the areas related to reward-processing as a consequence of their attempts to restrict their intake. Mild changes in grey matter volume can occur after behavioral interventions or training (Boyke, Driemeyer, Gaser, Buchel, & May, 2008; Krafnick, Flowers, Napoliello, & Eden, 2011; Holzel et al., 2011). States and behavior related to dieting attempts, such as weight-loss and hunger result in changes in hormones and homeostatic mechanisms which increase motivation to eat, and these effects may become stronger if people diet more frequently (Dulloo, Jacquet, Montani, & Schutz, 2015; Dulloo et al., 2015; Hooper et al., 2010; Pietilainen, Saarni, Kaprio, & Rissanen, 2012). An fMRI study that supports this idea is the study of Rosenbaum et al. (2008) that found that responses in areas associated with reward were higher after losing weight (compared to before weight loss). Longitudinal studies should investigate whether increased grey matter volume in reward-related areas is a predispositional factor or results from repeated periods of energy-deficit. This is important to know because it has important implications for weight-control interventions. If repeated periods of dietary restraint-related states and behaviors (e.g., temporary weight-loss, hunger) indeed result in small changes to regional grey matter volumes which predisposes people to be more reward sensitive or worse at inhibition, this would add further support to the growing body of evidence on adverse effects of dieting in lean individuals (Dulloo et al., 2015).

Although there is much evidence that the self-reported status of being a restrained eater is a marker for someone's intention rather than actual success in restricting food intake (French et al., 1994; Klesges et al., 1992; Lowe et al., 2013; Mann et al., 2007; Stice, Fisher et al., 2004; Stice et al., 2007, 2010; Tanofsky-Kraff et al., 2006; Williamson et al., 2007), it should be noted that we did not measure actual intake in our study sample. Future neuroanatomical studies should include measures of actual eating behavior to find out how grey matter volumes relate to actual success in restricting intake. Furthermore, it should be noted that we did not have independent measures of reward processing and inhibitory control in the present study. Consequently, some of our interpretations are based on reverse inference (e.g., proposing a role for reward processing because reward-related areas were identified

in the analyses) (Poldrack, 2011), which is a limitation of our study. Therefore, an important direction for future research is to include measures of reward processing and inhibitory capacity, in addition to self-reported dietary restraint.

For interpreting restraint-related individual differences in grey matter volume, it is important to know how brain structure, i.e., regional grey matter volume, relates to brain function. Currently, the direction of volume–function relations is not entirely certain, but in the adult population there is more evidence favoring the ‘higher volume – better performance’ position than the ‘lower volume – higher efficiency’ position (DeYoung et al., 2010; Kanai & Rees, 2011). There are many studies in adult populations that have shown that higher regional grey matter volumes are related to better functioning (for a review, see Kanai & Rees, 2011). For example, lower grey matter volume in the inferior frontal gyrus relates to poorer performance on a task measuring inhibitory capacity (Wiers et al., 2015). Furthermore, training on particular tasks has been shown to result in increases in grey matter volume of functionally relevant areas it is possible to make mild changes in grey matter volume by behavioral interventions or training (Boyke et al., 2008; Draganski & May, 2008; Kanai & Rees, 2011). For example, training on a visual motor coordination task increases grey matter volume of visual motion processing area V5 (Draganski & May, 2008). Although most studies in adults find a positive relation between regional grey matter volume and performance, there are also studies, particularly in adolescents, that found the opposite. This inverse relation is often explained by a developmental perspective: during adolescence, maturation of the cortex is accompanied by ‘pruning’ which means that the computational efficacy improves by the removal of weak synapses (Kanai & Rees, 2011). Because most evidence in adults favors the higher volume – better performance position, we interpreted our results conforming to this position. However, it remains an important topic for future research to determine the exact relation between regional grey matter volume and cognitive function.

To conclude, we found that individual differences in self-reported dietary restraint are associated with regional differences in grey matter volume. Our findings that dietary restraint is related to higher regional grey matter volumes in reward-related subcortical areas and lower regional grey matter volumes in a region involved in inhibition, provide a neuroanatomical underpinning for theories that predict that self-reported dietary restraint is related to increased reward sensitivity and reduced inhibitory control capacity.

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approved the final manuscript. None of the authors reported a conflict of interest related to the study.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.biopsycho.2016.03.007>.

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