Received: 13 June 2022 | Accepted: 29 July 2022

DOI: 10.1002/hbm.26059

RESEARCH ARTICLE

WILEY

The effect of hunger state on hypothalamic functional connectivity in response to food cues

Stephanie Kullmann[1,2] | Ralf Veit[1] | Daniel R. Crabtree[3,4] | William Buosi[3] | Odysseas Androutsos[5] | Alexandra M. Johnstone[3] | Yannis Manios[6] | Hubert Preissl[1,2] | Paul A. M. Smeets[7,8]

[1]Institute for Diabetes Research and Metabolic Diseases of the Helmholtz Center Munich at the University of Tübingen, German Center for Diabetes Research (DZD), Tübingen, Germany

[2]Department of Internal Medicine, Division of Diabetology, Endocrinology and Nephrology, Eberhard Karls University Tübingen, Tübingen, Germany

[3]The Rowett Institute, University of Aberdeen, Aberdeen, Scotland

[4]Division of Biomedical Sciences, Centre for Health Science, University of the Highlands and Islands, Inverness, UK

[5]Department of Nutrition and Dietetics, School of Physical Education, Sport Science and Dietetics, University of Thessaly, Volos, Greece

[6]Department of Nutrition-Dietetics, School of Health Science and Education, Harokopio University, Athens, Greece

[7]Division of Human Nutrition and Health, Wageningen University, Wageningen, The Netherlands

[8]Image Sciences Institute, University Medical Center Utrecht Brain Center, Utrecht University, Utrecht, The Netherlands

Correspondence
Stephanie Kullmann, Institute for Diabetes Research and Metabolic Diseases of the Helmholtz Center Munich, University of Tübingen, Tübingen, Germany.
Email: stephanie.kullmann@med.uni-tuebingen.de

Funding information
Federal Ministry of Education and Research to the German Center for Diabetes Research (DZD), Grant/Award Number: 01GI0925; FP7 Food, Agriculture and Fisheries, Biotechnology, Grant/Award Number: 266408; European Union Seventh Framework Programme

Abstract

The neural underpinnings of the integration of internal and external cues that reflect nutritional status are poorly understood in humans. The hypothalamus is a key integrative area involved in short- and long-term energy intake regulation. Hence, we examined the effect of hunger state on the hypothalamus network using functional magnetic resonance imaging. In a multicenter study, participants performed a food cue viewing task either fasted or sated on two separate days. We evaluated hypothalamic functional connectivity (FC) using psychophysiological interactions during high versus low caloric food cue viewing in 107 adults (divided into four groups based on age and body mass index [BMI]; age range 24–76 years; BMI range 19.5–41.5 kg/m^2). In the sated compared to the fasted condition, the hypothalamus showed significantly higher FC with the bilateral caudate, the left insula and parts of the left inferior frontal cortex. Interestingly, we observed a significant interaction between hunger state and BMI group in the dorsolateral prefrontal cortex (DLPFC). Participants with normal weight compared to overweight and obesity showed higher FC between the hypothalamus and DLPFC in the fasted condition. The current study showed that task-based FC of the hypothalamus can be modulated by internal (hunger state) and external cues (i.e., food cues with varying caloric content) with a general enhanced communication in the sated state and obesity-associated differences in

Stephanie Kullmann and Ralf Veit contributed equally to this study.

hypothalamus to DLPFC communication. This could potentially promote overeating in persons with obesity.

KEYWORDS
fMRI, food cue reactivity, functional connectivity, hunger, insulin resistance, obesity, satiety

1 | INTRODUCTION

As obesity rates keep increasing dramatically around the globe, actions are needed to support healthy diets and lifestyles. In our obesogenic environment, we are continuously exposed to highly appetizing food cues, which can promote overconsumption and weight gain (Ferriday & Brunstrom, 2008). Brain reactivity to food cues is associated with portion size selection (Hege et al., 2018; Veit et al., 2020), food choice, and food consumption (Christensen et al., 2021; Stice et al., 2008) and is even predictive for the outcome of weight-loss interventions (Hermann et al., 2019; Stice & Yokum, 2018).

Specifically, in neuroimaging studies, food cue reactivity (FCR) tasks are used to examine brain responses to food images depending on caloric content, palatability, healthiness, macronutrient content, or level of processing (Smeets et al., 2019). In healthy individuals, food images activate the so-called appetitive brain network, which includes the amygdala, striatum, insula and the orbitofrontal cortex (OFC) (Neseliler et al., 2017). High compared to LC foods elicit differential activation in the ventral striatum, hypothalamus, the left frontal and occipital cortex, and the right inferior temporal region. These areas are involved in reward processing and homeostasis but also in visual processing and executive function (Neseliler et al., 2017). Persons with obesity respond to palatable food cues with heightened FCR in brain regions important for reward and gustatory processing (Christensen et al., 2021; Devoto et al., 2018; Kenny, 2011; Pursey et al., 2014; Stice et al., 2008). In contrast, brain regions important for cognitive control have been found to be less responsive in persons with obesity (Brooks et al., 2013; Christensen et al., 2021; Han et al., 2018). However, this view of heightened incentive salience of food cues in obesity was recently challenged. A meta-analysis, by Morys et al. (2020) failed to identify consistent differences in FCR between normal weight and overweight/obese groups. These findings point to additional factors that could mediate the FCR activation pattern. In particular, sex, age, hunger state, body mass index (BMI) and food stimulus type may significantly influence FCR activation patterns (Bennett et al., 2021; Charbonnier et al., 2018; Smeets et al., 2019; Wever et al., 2021). With increasing age, the insular cortex is less responsive to food cues, while FCR in the fusiform gyrus, a higher visual area, showed stronger activity with increasing age (Morys et al., 2020).

Hunger can lead to increased reactivity to food cues in primary and higher level visual processing areas in normal weight individuals (Charbonnier et al., 2018; Fuhrer et al., 2008; Siep et al., 2009; Uher et al., 2006). Moreover, in a fasted state, high opposed to low-caloric food images elicit stronger activity in the appetitive brain network (Goldstone et al., 2009; Mehta et al., 2012; van der Laan et al., 2011). Persons with obesity tend to show higher FCR when sated in areas involved in executive function, reward and emotional processing compared to lean counterparts (Devoto et al., 2018; Pursey et al., 2014), particularly in the ventral striatum (Devoto et al., 2018).

Relatively little is known about the role of the hypothalamus in response to visual food-cues. The hypothalamus is a key integrative area involved in the control of basic life functions including short- and long-term energy intake regulation. Distinct nuclei in the hypothalamus are involved in the control of food intake with specific roles in the processing of hunger and satiation (Berthoud & Munzberg, 2011; Hetherington & Ranson, 1942). These include the ventromedial, the lateral, and the dorsomedial hypothalamus as well as the arcuate and paraventricular nuclei (Nieuwenhuys et al., 2008). In humans, resting-state fMRI studies showed that the hypothalamus is functionally coupled to the regions of the appetitive brain network (Kullmann et al., 2014; Kullmann & Veit, 2021). Particularly, the influence of fasting has been investigated on hypothalamus resting-state functional connectivity showing higher functional connectivity to the medial PFC (Lips et al., 2014; van de Sande-Lee et al., 2011; Wijngaarden et al., 2015; Wright et al., 2016) and insula cortex (Lips et al., 2014; Wijngaarden et al., 2015) in persons of normal weight. An overall reduction in hypothalamic functional connectivity was observed in the sated compared to the fasted state (Lips et al., 2014; Sewaybricker et al., 2020). This effect was less pronounced in persons with overweight and obesity (Lips et al., 2014).

With the current study, we investigated task-based functional connectivity of the hypothalamus network by using high and low-caloric (HC and LC) food images in a fasted and sated condition in males and females of different age and weight groups. We hypothesized that hypothalamic functional connectivity is higher with reward and gustatory related regions in the fasted compared to the sated state during the visual FCR task (HC minus LC food images). In normal weight participants, we expected higher FC between the hypothalamus and the dorsolateral prefrontal cortex (DLPFC), while participants with overweight/obesity were expected to show higher hypothalamus FC to reward related brain region, particular in the fasted state. In the elderly group, we hypothesized a decline in hypothalamic FC independent of hunger state. In exploratory analyses, we investigated associations between hypothalamic FC and peripheral insulin resistance as well as experienced fullness and hunger.

TABLE 1 Participant characteristics

		Female	Male		
Sex (count)	Adult NW	16	13		
	Elderly NW	15	10		
	Adult OW/Ob	11	16		
	Elderly OW/Ob	15	11		
	All	57	50		
		Mean	*SD*	*Min*	*Max*
Age in years	Adult NW	33.41	6.92	25.03	47.25
	Elderly NW	70.04	3.11	64.96	76.11
	Adult OW/Ob	35.26	6.69	24.21	45.85
	Elderly OW/Ob	67.31	3.16	61.95	74.88
	All	50.67	18.07	24.21	76.11
Body mass index (kg/m^2)	Adult NW	22.95	1.85	19.74	26.10
	Elderly NW	23.51	1.98	19.52	26.58
	Adult OW/Ob	30.99	3.27	27	41.49
	Elderly OW/Ob	31.35	2.92	26.85	36.29
	All	27.11	4.73	19.52	41.49
HOMA-IR	Adult NW	1.38	0.80	0.44	4.04
	Elderly NW	1.68	1.10	0.30	5.33
	Adult OW/Ob	3.72	2.16	1.11	10.54
	Elderly OW/Ob	3.97	1.93	1.30	10.55
	All	2.67	1.96	0.30	10.55

Abbreviations: NW, normal weight; OW/Ob, overweight/obese.

2 | METHODS

2.1 | Participants

As part of the European Full4Health project (https://www.abdn.ac.uk/rowett/research/full4health.php) functional MRI measurements were performed in three different countries (The Netherlands, Scotland, and Greece). In the present study, we included healthy adults of normal-weight (BMI 20–25 kg/m^2), overweight and obesity (BMI ≥27.5 kg/m^2) with two different age ranges (adult: 20–50 years, elderly: >60 years). Participants were categorized into four groups based on their BMI and age (normal-weight adults, normal-weight elderly, overweight/obese adults, and overweight/obese elderly). Only right-handed, nonsmoking participants without major weight fluctuation (±5 kg) in the last 6 months were included in the study. Medication (except aspirin/paracetamol and oral contraceptives and anticoagulants and cholesterol medication in elderly) and no excessive alcohol consumption (>28 units per week) was allowed. Furthermore, participants with disturbed eating behavior (measured with Dutch Eating Behavior Questionnaire (Van Strien et al., 1986)) food allergies, special diets, eating disorders as well as metabolic syndrome, endocrine disease and gastrointestinal disorders were excluded. Moreover, the participants had to fulfill the inclusion criteria for MRI measurements (e.g., no metal implants).

A total of 133 participants were enrolled in the study. After data quality control (see below), 107 participants (57 women, 50 men; BMI range 19.5–41.5 kg/m^2; age range 24.2–76.1 years) were included in the final data analyses (see Table 1 for participants' characteristics). The study was registered at NTR (trialregister.nl).

2.2 | Study procedures

After an overnight fast, participants came on two separate mornings for an MRI scanning session (sated and fasted condition). The MRI sessions were counterbalanced and separated by 1–2 weeks. In the sated condition, participants were scanned 1 h after consumption of a fixed amount of liquid meal (for details, see (Charbonnier et al., 2018)). On both days, a blood sample was taken followed by an FCR task in the MRI scanner. Hunger and fullness were rated at baseline after an overnight fast, at 30 min (after liquid breakfast or no breakfast) and at 55 min (before the food viewing task) using 9-point Likert scales. For more details on study design, see recent publications (Charbonnier et al., 2018; Wever et al., 2021).

2.3 | Food cue viewing fMRI task

The FCR task consisted of six blocks with HC food, six blocks with LC food, and six blocks with nonfood (NF) items. Each block included seven images and lasted for 20.5 s, the interblock interval varied between 3.5 and 4 s. The order of the blocks was kept

constant over the course of the task (LC, NF, HC). The images were selected from a standardized image set (Charbonnier et al., 2016) and were adapted to ensure recognizability and liking in each of the three countries. The imaging viewing task lasted 442 s in total. At the beginning of the experiment, the participants received the following task instruction: "In the next task you will see food and non-food products. Please look at the images and pay close attention, since at the end of the MRI session you will be asked a couple of questions regarding the images shown during this task." After the MRI session, participants were shown 10 images for which they had to indicate whether they had seen them during the task. See Charbonnier et al. (2018) for more details.

2.4 | Image acquisition and processing

Scanning was performed on a Philips Achieva 3.0 T MRI scanner (Philips Healthcare, Best, NL) in all three countries. Functional images were obtained with an eight-channel SENSE head-coil using a 2D echo planar imaging sequence with the following parameters: voxel size 4 mm isotropic; repetition time (TR) = 1400 ms; echo time = 23 ms; flip angle = 70°; 30 axial slices; SENSE-factor = 2.4 (anterior–posterior). Then, 316 functional images were acquired. A high-resolution anatomical image (T_1-weighted scan) was acquired at $1 \times 1 \times 1$ mm^3 resolution.

2.5 | Image preprocessing

Spatial and temporal preprocessing and statistical analyses were carried out with SPM12 (http://www.fil.ion.ucl.ac.uk/spm). Slice timing correction and realignment was performed for each fMRI time series, and the structural scan was coregistered to the mean functional image. The T1 weighted anatomical image was segmented using unified segmentation, and normalization parameters were estimated. The elderly group did not show any apparent brain abnormalities or damages; hence, we used a common template created using DARTEL for all participants, which is considered more robust for normalization. The template was used to normalize the functional scans to MNI space. The data were then smoothed with an isotropic 8-mm full width at half maximum Gaussian kernel. The ArtRepair toolbox (http://cibsr.stanford.edu/tools/ArtRepair/ArtRepair.htm) was applied to detect and repair anomalously noisy volumes. Volumes that moved more than 1 mm/TR were repaired.

2.6 | Subject level analyses

For each participant, a design matrix was created with the regressors HC food, LC food, and NF, separately for the two conditions (fasted/sated). Each regressor was convolved with a canonical hemodynamic response function. Data were high-pass filtered with a cutoff of 128 s and low-pass filtered (Autoregression Model AR(1)). The following contrasts were created: HC minus LC food images, food images (HC and LC combined) minus NF images.

A visual inspection of the activation maps (T-maps) during image viewing revealed datasets with minimal or no activation. Therefore, we adopted a specific quality criterion, which was already applied in the same multicenter study (Wever et al., 2021). We calculated the number of voxels with significant brain activity at $p < .001$ in a composite mask including the fusiform gyrus, lingual gyrus, occipital gyrus, and extended visual cortex based on the automated anatomical labeling (AAL) atlas, separately for the 2 days. Only participants that exceeded the 10% percentile of active voxels (cut off: 224 voxels) on both days were included in the analysis. A total of 21 participants were below this threshold on one or two visits and five participants were excluded based on incomplete brain coverage during fMRI recording. The final sample of 107 participants had 853 ± 326 significant voxels in the visual cortex ROI.

2.7 | Generalized psychophysiological interaction

A generalized psychophysiological interaction (gPPI) analysis (McLaren et al., 2012) (https://www.nitrc.org/projects/gppi version 13.1) was conducted to investigate task-related functional connectivity of the hypothalamus with other brain regions, for each measurement day (fasted/sated). We generated a mask of the hypothalamic nuclei related to energy regulation using the Neudorfer hypothalamus atlas (Neudorfer et al., 2020) including the lateral hypothalamus, the ventromedial hypothalamus, the dorsomedial hypothalamus, the arcuate, and the paraventricular nuclei. First, we created a combined mask of the regions and then resampled the masks to the dimension and voxel size of the AAL atlas 3 (AAL3 (Rolls et al., 2020); dimensions:

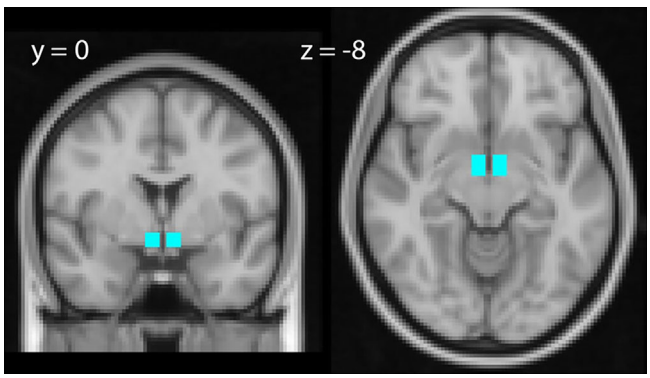

FIGURE 1 Hypothalamus mask applied in the generalized psychophysiological interactions (gPPI) analysis overlaid on a study-specific T1 weighted image in MNI space. Hypothalamus mask was created based on the Neudorfer hypothalamus atlas including the lateral hypothalamus, the ventromedial hypothalamus, the dorsomedial hypothalamus, the arcuate, and the paraventricular nuclei.

91 × 109 × 91, voxel size: 2 × 2 × 2 mm^3). In the next step, we resampled the mask to a voxel size of 4 mm^3. Using these approaches, a total of 3 × 8 voxels covered this mask (Figure 1).

Opposed to the traditional PPI approach, the generalized PPI allows the integration of several interaction vectors in the design matrix. The time series for each seed region was extracted using the first eigenvariate. To adjust for non-task regressors an omnibus *F*-test was performed in the original first level analysis. This allows removal of nonneural sources (e.g., motion) before deconvolution of the signal. In a next step, for each condition, a PPI interaction term was created (HC food, LC food, NF). The inclusion of all conditions in the design matrix allows a better estimate of the underlying psychophysiological interactions. Finally, a contrast vector was created testing the effect of caloric content (HC minus LC food images).

2.8 | Second-level group analysis

The resulting contrast images (HC minus LC food) were entered into a second level full-factorial model with the within-subject factor: hunger condition (fasted vs. sated), and between subject-factor: BMI group (lean vs. overweight/obese) and age group (adult vs. elderly). As covariates of no interest, the country site (dummy coded with two regressors) and sex (female/male) were included in the design matrix.

In a separate exploratory analysis, we investigated the effect of sex as additional categorical factor. Here, we used age as a continuous covariate in the design matrix. The factors hunger condition and BMI group were the same as in the above mentioned analyses.

A statistical threshold of $p < .001$ uncorrected and a $p < .05$ family wise error (FWE) corrected for multiple comparisons at a cluster level was applied. We used the SPM Cluster Threshold toolbox (https://github.com/CyclotronResearchCentre/SPM_ClusterSizeThreshold) to compute the minimum number of voxels determining a significant cluster. Significant activations that survived FWE correction at a peak level ($p_{FWE} < .05$) were also reported. Additionally, small volume correction was performed for the striatum (putamen, pallidum, caudate), insula and the DLPFC, as they are a priori regions of interest due to their involvement in food-cue processing (Neseliler et al., 2017). The masks were based on the AAL atlas 3 (https://www.oxcns.org) and the *wfu* pick atlas (https://www.nitrc.org/projects/wfu_pickatlas/) (Maldjian et al., 2003). For the DLPFC, we used a mask created by Matthjis Vink (https://matthijs-vink.com/my-open-science). Correction for multiple comparisons for small volume correction was restricted to the masks (Bonferroni corrected for the number of ROI's; corrected threshold $p = .016$).

To investigate to which extent other important factors as experienced hunger and fullness and markers of peripheral insulin resistance (HOMA-IR) modulated the FC pattern, the connectivity parameters (beta estimates) of significant clusters were extracted for additional correlation analyses.

2.9 | Results

2.10 | gPPI analyses of the hypothalamus network in response to HC compared to LC food cues

2.10.1 | Hypothalamus functional connectivity network

We observed higher functional connectivity between the hypothalamus and the bilateral caudate in the sated compared to the fasted state (Figure 2a). The cluster of the left caudate extended into the left insula, the left frontal inferior triangularis, and the left frontal inferior operculum. There was a significant BMI group × hunger state interaction in the right DLPFC, the left middle occipital gyrus, and the left precentral gyrus (Table 2). Post hoc contrasts showed that participants with normal weight compared to participants with overweight/obesity exhibited stronger FC between hypothalamus and the right DLPFC (Figure 3), left insula and middle occipital gyrus in the fasted but not in the sated state (Table 2, Figure 2b). There was no main effect of age group. There were no two-way interactions between age group and hunger state and no significant three-way interaction.

2.10.2 | Effect of sex on hypothalamic functional connectivity

In exploratory analyses, there was no main effect of sex or interaction with hunger state or BMI group in the full factorial analyses adjusted for age (all $p > .05$).

2.10.3 | Correlation analyses of hypothalamus network with fullness and hunger ratings

For the sated day, the hypothalamus to right caudate connection significantly correlated with the change in fullness ratings (from before to after the liquid meal) adjusted for sex, age, and BMI ($r = -.272$, $p_{adj} = .009$). Hence, participants showing an increase in experienced fullness show lower functional connectivity between the hypothalamus and caudate on the sated day.

2.10.4 | Correlation analyses of hypothalamus network with HOMA-IR

The differential (sated minus fasted condition) functional connectivity between the hypothalamus and left caudate correlated with HOMA-IR ($r = .214$, $p = .032$ adjusted for sex and age). Hence, participants with insulin resistance showed stronger FC between the hypothalamus and the caudate in the sated compared to the fasted state in response to HC versus LC food cues.

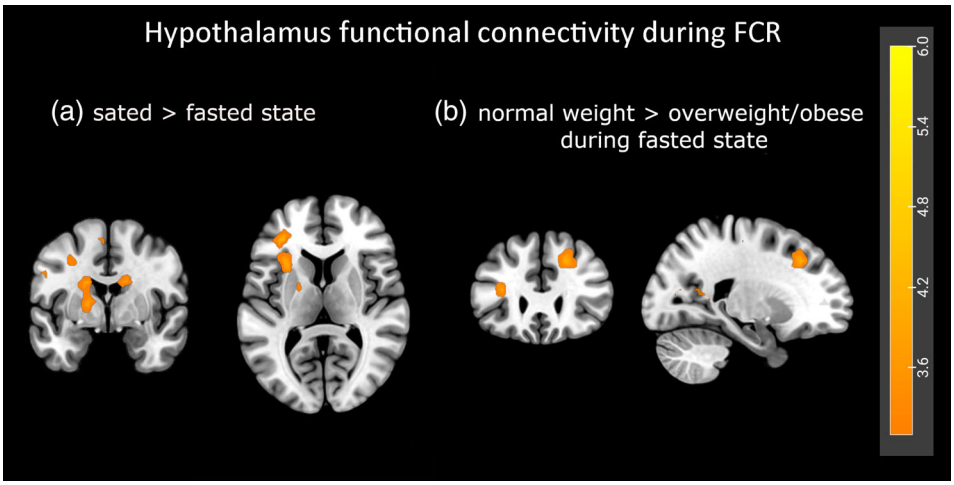

FIGURE 2 Hypothalamus task-based functional connectivity network. (a) Shown are clusters of the hypothalamus network revealing higher functional connectivity in the sated versus the fasted state. (b) Shown are clusters of the hypothalamus network revealing higher functional connectivity in normal weight in comparison to overweight/obese participants during the fasted state. Color maps correspond to *t*-values (thresholded at $t = 3.13/p < 001$ uncorrected for display).

TABLE 2 Hypothalamus functional connectivity network in response to high versus low caloric food cues

Brain region	Hemi	MNI coordinates x	y	z	Peak *t*	p_{FWE}
Sated > fasted						
Caudate	L	−16	12	20	4.94	<.001
Caudate	R	16	4	24	3.82	.027[SVC]
Frontal inferior triangular part	L	−32	36	12	4.76	<.001
Insula[a]	L	−32	20	12	4.82	.013
Precentral gyrus/frontal Inferior operculum	L	−56	8	28	3.87	.043
Fasted > sated						
No differential activation	--	--	--	--	--	--
Overweight/obese vs. normal weight						
No differential activation	--	--	--	--	--	--
Interaction hunger state × BMI status						
Superior frontal (DLPFC)	R	20	28	40	4.54	.039
Precentral gyrus	L	−36	−12	36	4.07	.002
Middle occipital	L	−24	−96	4	4.04	.006
Post hoc contrasts						
Normal weight > overweight/obese fasted state						
Superior frontal (DLPFC)	R	20	28	40	4.42	.004[SVC]
Insula	L	−28	28	12	4.37	<.001
Frontal inferior triangularis (DLPFC)	R	44	20	24	3.91	.024[SVC]
Middle occipital	L	−40	−64	8	3.78	.022
Normal weight < overweight/obese sated state						
No differential activation	--	--	--	--	--	--
Normal weight < overweight/obese fasted state						
No differential activation	--	--	--	--	--	--
Normal weight > overweight/obese sated state						
	--	--	--	--	--	--

Abbreviations: BMI, body mass index; DLPFC, dorsolateral prefrontal cortex; FWE, family wise error.
[a]The insula is part of the same cluster as the frontal inferior triangularis, but shows also significant differential connectivity on a peak level ($p < .05$ FWE corrected). Hemi = hemisphere, L = left, R = right; *p* value FWE corrected using whole-brain cluster correction, the cluster size threshold for the analyses was 47 voxels; SVC p_{FWE} small volume corrected for ROIs.

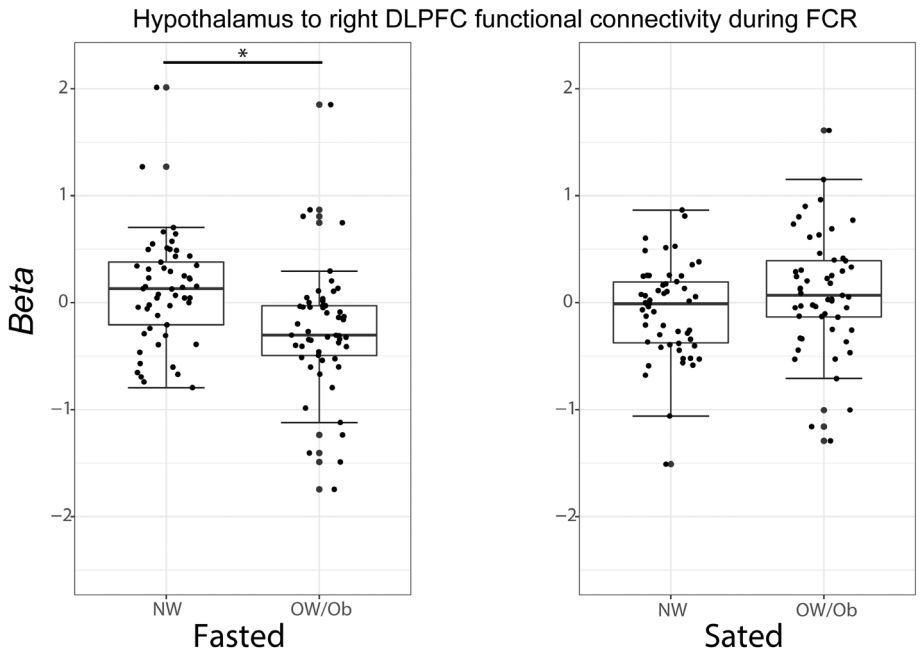

FIGURE 3 Box plot showing hypothalamic functional connectivity (y-axes: beta estimates) to the right dorsolateral prefrontal cortex (DLPFC) in the fasted and sated state during food cue reactivity (FCR) in normal-weight (NW) and overweight/obese (OW/Ob) participants. A two-way interaction between hunger state and body mass index (BMI) group was identified in parts of the right DLPFC ($p_{FWE} < .05$). In the fasted state, NW participants showed higher functional connectivity between the hypothalamus and the right DLPFC than the OW/Ob group. No group differences were observed in the sated state.

2.10.5 | General linear model and gPPI of FCR (based on HC minus LC food cue contrast)

In order to compare our FCR results with previous findings, a second level group analysis was carried out using the HC minus LC contrast to evaluate changes in regional task-related brain activity. We found stronger activations in the caudate, insula, anterior cingulate, and OFC for HC minus LC food stimuli (Supplementary Table 1 and Supplementary Figure 1) with higher activity in the putamen, caudate and pallidum in the fasted compared to the sated state. Additional gPPI analyses were carried out to investigate task-related functional connectivity based on the reported HC minus LC activity changes in the FCR task (using the seeds: left caudate, right caudate, left insula, left ACC). Overall, we found higher task-based functional connectivity in the caudate, insula, anterior cingulate, and OFC in the sated compared to the fasted state (for more information, see Supplementary Material).

3 | DISCUSSION

The aim of the current study was to investigate task-based functional connectivity patterns of the hypothalamus in the sated compared to the fasted state in response to food images with varying caloric content. When viewing HC compared to LC food cues, we could confirm higher activity in the insula, anterior cingulate, OFC and caudate, as previously reported (Neseliler et al., 2017). Based on previous studies, we postulated that task-based hypothalamic functional connectivity would be higher in the fasted state during the evaluation of HC food cues. Contrary to our hypothesis, we found higher hypothalamic functional connectivity, in the sated compared to the fasted state, with brain regions involved in reward and gustatory processing and executive function. However, we found a significant interaction between BMI status and hunger state in the right DLPFC. The coupling between hypothalamus and right DLPFC was strongest in persons with normal weight compared to persons with overweight/obese in the fasted state. As hypothesized, peripheral metabolism and subjective ratings of fullness correlated with hypothalamic functional connectivity.

We observed higher functional connectivity between the hypothalamus to striatal regions, and primary and secondary gustatory cortices in the sated condition. Functional coupling between the homeostatic regions of the brain and reward and taste processing areas was strengthened after a meal when evaluating HC in comparison to LC food cues. Concurrently, glucose, sucrose, and fat ingestion increased resting-state functional connectivity of the hypothalamus to the striatum (Page et al., 2013) and insular cortex (Frank-Podlech et al., 2019; Kilpatrick et al., 2014). In the current study, the hypothalamus network showed the greatest differences in functional coupling between the sated and the fasted state. Sensory information such as visual food cues and internal signals from the periphery reflecting the current hunger state have been postulated to converge in the insula and higher cortical areas and to influence food choice and eating behavior (de Araujo et al., 2020). In our study, satiation strengthened the hypothalamic functional connections in response to HC food images. This could indicate that in the sated state communication is enhanced in the hypothalamus network specifically to the striatum and the gustatory cortex (i.e., insula and frontal operculum). Independent of nutritional state, a recent systematic review on resting-state fMRI showed higher hypothalamus functional connectivity to reward brain regions and lower functional connectivity to cognitive regions in persons with obesity (Syan et al., 2021). Concomitantly, in the current study, the hypothalamus connections particularly to the caudate nucleus was affected by experienced fullness and metabolic health

showing stronger functional coupling in persons with greater insulin resistance (based on HOMA-IR). This corresponds with FCR studies showing an increased activation of striatal regions with higher HOMA-IR values (Drummen et al., 2019; Jastreboff et al., 2013). Moreover, insulin is thought to play a pivotal role in brain reward regulation by modulating dopamine function in the striatum (Kullmann et al., 2021), thereby decreasing food palatability ratings and food intake (Kullmann et al., 2015; Tiedemann et al., 2017). In people with insulin resistance, insulin action in the dopaminergic circuitry is disturbed, which is related to higher preference for palatable foods (Kullmann et al., 2020). Hence, disturbances in reward function may lead to overeating and facilitate the transition from obesity-associated insulin resistance to the development of type 2 diabetes.

Hypothalamus connectivity with cognitive regions (i.e., the DLPFC) was affected by weight status in the hungry but not sated state. Adults and elderly of normal weight showed higher hypothalamus to DLPFC connectivity when viewing HC compared to LC food cues. Similarly, Charbonnier et al. (2018) showed greater DLPFC activity to HC versus LC cues in the fasted compared of sated state independent of age. DLPFC recruitment is vital for healthy food choices and dietary self-control (Hare et al., 2009; Hare et al., 2011; Kohl et al., 2019; Lowe et al., 2019; van Meer et al., 2017; van Meer et al., 2019). In persons with overweight/obesity, previous studies have shown diminished DLPFC activity in response to food cues (Brooks et al., 2013; Christensen et al., 2021; Veit et al., 2021) as well as reduced hypothalamus to DLPFC connectivity (Syan et al., 2021). Internal and external signals can facilitate an increase in hypothalamic functional connectivity to the PFC. The hormonal satiety signal insulin (Kullmann et al., 2017) and the choice of healthy food items enhanced hypothalamus PFC connectivity (Harding et al., 2018). Whether higher hypothalamic functional connectivity to the DLPFC is linked to better dietary self-control is currently not known. Future studies need to evaluate whether the hypothalamus network that responds to HC food cues can predict food choice behavior, food consumption, or metabolism.

4 | LIMITATIONS

Our study sample included a large BMI range, but due to the limited sample size, we were not able to evaluate whether persons with overweight versus obesity may show separable hypothalamus FC patterns. It is currently not clear whether our findings can be generalized to resting-state functional connectivity patterns. Recent studies investigating the interplay of the hypothalamus under different nutritional states and hormonal manipulations primarily used resting-state fMRI (Kullmann & Veit, 2021). Only few studies examined task-evoked and task-independent resting-state functional connectivity within the same sample (Donofry et al., 2020; Lynch et al., 2018; Mehl et al., 2019), however, with different seed regions. Donofry et al. (2020) investigated food-cue induced and resting-state functional connectivity showing a dissociable pattern in persons with overweight and obesity. Higher BMI was associated with weaker functional connectivity during rest and higher functional connectivity in response to HC food cues (Donofry et al., 2020). This suggests context-dependent functional connectivity among individuals who are overweight and obese. In line with this contextualization, there is evidence that engaging in a task may suppress resting-state functional connectivity (Lynch et al., 2018). Hence, hypothalamus communication during resting-state state may lead to different results in the sated compared to the fasted state as observed in the current study. Further studies are needed to disentangle internal and externals cue integration on the hypothalamic functional connectivity profile during task-based and resting-state fMRI.

5 | CONCLUSION

The current study shows that brain functional connectivity is modulated by internal as well as external cues. While viewing HC foods, hypothalamic functional connectivity to reward and cognitive regions of the brain was higher in the sated state. Lower functional coupling to the prefrontal cortex was observed in participants with obesity. This could potentially promote overeating and accelerate the transition to metabolic diseases as type 2 diabetes. Whether hypothalamus connectivity profiles are related to overeating and weight gain still needs to be investigated.

AUTHOR CONTRIBUTIONS

Stephanie Kullmann: Conceptualization; formal analysis; writing - original draft; writing - review and editing. Ralf Veit: Formal analysis; methodology; roles/writing - original draft; writing - review and editing. Daniel R. Crabtree: Investigation; writing - review and editing. William Buosi: Investigation; writing - review and editing. Odysseas Androutsos: Investigation; supervision; writing - review and editing. Alexandra M. Johnstone: Funding acquisition; resources; investigation; supervision; writing - review and editing. Yannis Manios: Funding acquisition; resources; investigation; supervision; writing - review and editing. Hubert Preissl: Funding acquisition; resources; investigation; supervision; writing - review and editing. Paul A. M. Smeets: Funding acquisition; conceptualization; resources; investigation; methodology; project administration; supervision; roles/writing - original draft; writing - review and editing; data curation.

ACKNOWLEDGMENT

The authors thank Lisette Charbonnier for her relentless efforts in setting up the study at all three sites and collecting the Dutch data. Open Access funding enabled and organized by Projekt DEAL.

FUNDING INFORMATION

This work was financially supported by the European Union Seventh Framework Programme (FP7/2007–2013) for research, technological development, and demonstration under grant agreement 266408 (Full4Health, www.full4health.eu). Furthermore, the study was supported in parts by a grant (01GI0925) from the Federal Ministry of Education and Research (BMBF) to the German Center for Diabetes Research (DZD e.V.).

DATA AVAILABILITY STATEMENT

The authors have documented all data, methods, and materials used to conduct this research study, and anonymized data will be shared by request from any qualified investigator.

PATENT CONSENT STATEMENT

All participants provided written informed consent.

ORCID

Stephanie Kullmann https://orcid.org/0000-0001-9951-923X
Hubert Preissl https://orcid.org/0000-0002-8859-4661
Paul A. M. Smeets https://orcid.org/0000-0002-8695-9612

REFERENCES

Bennett, C., Burrows, T., Pursey, K., Poudel, G., Ng, K. W., Nguo, K., Walker, K., & Porter, J. (2021). Neural responses to food cues in middle to older aged adults: A scoping review of fMRI studies. *Nutrition and Dietetics*, *78*, 343–364.

Berthoud, H. R., & Munzberg, H. (2011). The lateral hypothalamus as integrator of metabolic and environmental needs: From electrical self-stimulation to opto-genetics. *Physiology & Behavior*, *104*, 29–39.

Brooks, S. J., Cedernaes, J., & Schioth, H. B. (2013). Increased prefrontal and parahippocampal activation with reduced dorsolateral prefrontal and insular cortex activation to food images in obesity: A meta-analysis of fMRI studies. *PLoS One*, *8*, e60393.

Charbonnier, L., van Meer, F., Johnstone, A. M., Crabtree, D., Buosi, W., Manios, Y., Androutsos, O., Giannopoulou, A., Viergever, M. A., Smeets, P. A. M., & Full4Health Consortium. (2018). Effects of hunger state on the brain responses to food cues across the life span. *NeuroImage*, *171*, 246–255.

Charbonnier, L., van Meer, F., van der Laan, L. N., Viergever, M. A., & Smeets, P. A. M. (2016). Standardized food images: A photographing protocol and image database. *Appetite*, *96*, 166–173.

Christensen, E. L., Harding, I. H., Voigt, K., Chong, T. T., & Verdejo-Garcia, A. (2021). Neural underpinnings of food choice and consumption in obesity. *International Journal of Obesity*, *46*, 194–201.

de Araujo, I. E., Schatzker, M., & Small, D. M. (2020). Rethinking food reward. *Annual Review of Psychology*, *71*, 139–164.

Devoto, F., Zapparoli, L., Bonandrini, R., Berlingeri, M., Ferrulli, A., Luzi, L., Banfi, G., & Paulesu, E. (2018). Hungry brains: A meta-analytical review of brain activation imaging studies on food perception and appetite in obese individuals. *Neuroscience and Biobehavioral Reviews*, *94*, 271–285.

Donofry, S. D., Jakicic, J. M., Rogers, R. J., Watt, J. C., Roecklein, K. A., & Erickson, K. I. (2020). Comparison of food cue-evoked and resting-state functional connectivity in obesity. *Psychosomatic Medicine*, *82*, 261–271.

Drummen, M., Dorenbos, E., Vreugdenhil, A. C. E., Raben, A., Westerterp-Plantenga, M. S., & Adam, T. C. (2019). Insulin resistance, weight, and behavioral variables as determinants of brain reactivity to food cues: A prevention of diabetes through lifestyle intervention and population studies in Europe and around the world—A PREVIEW study. *The American Journal of Clinical Nutrition*, *109*, 315–321.

Ferriday, D., & Brunstrom, J. M. (2008). How does food-cue exposure lead to larger meal sizes? *The British Journal of Nutrition*, *100*, 1325–1332.

Frank-Podlech, S., Heinze, J. M., Machann, J., Scheffler, K., Camps, G., Fritsche, A., Rosenberger, M., Hinrichs, J., Veit, R., & Preissl, H. (2019). Functional connectivity within the gustatory network is altered by fat content and oral fat sensitivity—A pilot study. *Frontiers in Neuroscience*, *13*, 725.

Fuhrer, D., Zysset, S., & Stumvoll, M. (2008). Brain activity in hunger and satiety: An exploratory visually stimulated FMRI study. *Obesity (Silver Spring)*, *16*, 945–950.

Goldstone, A. P., Prechtl de Hernandez, C. G., Beaver, J. D., Muhammed, K., Croese, C., Bell, G., Durighel, G., Hughes, E., Waldman, A. D., Frost, G., & Bell, J. D. (2009). Fasting biases brain reward systems towards high-calorie foods. *The European Journal of Neuroscience*, *30*, 1625–1635.

Han, J. E., Boachie, N., Garcia-Garcia, I., Michaud, A., & Dagher, A. (2018). Neural correlates of dietary self-control in healthy adults: A meta-analysis of functional brain imaging studies. *Physiology & Behavior*, *192*, 98–108.

Harding, I. H., Andrews, Z. B., Mata, F., Orlandea, S., Martinez-Zalacain, I., Soriano-Mas, C., Stice, E., & Verdejo-Garcia, A. (2018). Brain substrates of unhealthy versus healthy food choices: Influence of homeostatic status and body mass index. *International Journal of Obesity*, *42*, 448–454.

Hare, T. A., Camerer, C. F., & Rangel, A. (2009). Self-control in decision-making involves modulation of the vmPFC valuation system. *Science*, *324*, 646–648.

Hare, T. A., Malmaud, J., & Rangel, A. (2011). Focusing attention on the health aspects of foods changes value signals in vmPFC and improves dietary choice. *The Journal of Neuroscience*, *31*, 11077–11087.

Hege, M. A., Veit, R., Krumsiek, J., Kullmann, S., Heni, M., Rogers, P. J., Brunstrom, J. M., Fritsche, A., & Preissl, H. (2018). Eating less or more—Mindset induced changes in neural correlates of pre-meal planning. *Appetite*, *125*, 492–501.

Hermann, P., Gal, V., Kobor, I., Kirwan, C. B., Kovacs, P., Kitka, T., Lengyel, Z., Balint, E., Varga, B., Cseko, C., & Vidnyanszky, Z. (2019). Efficacy of weight loss intervention can be predicted based on early alterations of fMRI food cue reactivity in the striatum. *NeuroImage: Clinical*, *23*, 101803.

Hetherington, A. W., & Ranson, S. W. (1942). The relation of various hypothalamic lesions to adiposity in the rat. *The Journal of Comparative Neurology*, *76*, 475–499.

Jastreboff, A. M., Sinha, R., Lacadie, C., Small, D. M., Sherwin, R. S., & Potenza, M. N. (2013). Neural correlates of stress- and food cue-induced food craving in obesity: Association with insulin levels. *Diabetes Care*, *36*, 394–402.

Kenny, P. J. (2011). Reward mechanisms in obesity: New insights and future directions. *Neuron*, *69*, 664–679.

Kilpatrick, L. A., Coveleskie, K., Connolly, L., Labus, J. S., Ebrat, B., Stains, J., Jiang, Z., Suyenobu, B. Y., Raybould, H. E., Tillisch, K., & Mayer, E. A. (2014). Influence of sucrose ingestion on brainstem and hypothalamic intrinsic oscillations in lean and obese women. *Gastroenterology*, *146*, 1212–1221.

Kohl, S. H., Veit, R., Spetter, M. S., Gunther, A., Rina, A., Luhrs, M., Birbaumer, N., Preissl, H., & Hallschmid, M. (2019). Real-time fMRI neurofeedback training to improve eating behavior by self-regulation of the dorsolateral prefrontal cortex: A randomized controlled trial in overweight and obese subjects. *NeuroImage*, *191*, 596–609.

Kullmann, S., Blum, D., Jaghutriz, B. A., Gassenmaier, C., Bender, B., Häring, H. U., Reischl, G., Preissl, H., la Fougère, C., Fritsche, A., Reimold, M., & Heni, M. (2021). Central insulin modulates dopamine signaling in the human striatum. *The Journal of Clinical Endocrinology and Metabolism*, *106*, 2949–2961.

Kullmann, S., Heni, M., Linder, K., Zipfel, S., Haring, H. U., Veit, R., Fritsche, A., & Preissl, H. (2014). Resting-state functional connectivity of the human hypothalamus. *Human Brain Mapping*, *35*, 6088–6096.

Kullmann, S., Heni, M., Veit, R., Scheffler, K., Machann, J., Haring, H. U., Fritsche, A., & Preissl, H. (2015). Selective insulin resistance in homeostatic and cognitive control brain areas in overweight and obese adults. *Diabetes Care*, *38*, 1044–1050.

Kullmann, S., Heni, M., Veit, R., Scheffler, K., Machann, J., Haring, H. U., Fritsche, A., & Preissl, H. (2017). Intranasal insulin enhances brain functional connectivity mediating the relationship

between adiposity and subjective feeling of hunger. *Scientific Reports*, *7*, 1627.

Kullmann, S., Kleinridders, A., Small, D. M., Fritsche, A., Haring, H. U., Preissl, H., & Heni, M. (2020). Central nervous pathways of insulin action in the control of metabolism and food intake. *The Lancet Diabetes and Endocrinology*, *8*, 524–534.

Kullmann, S., & Veit, R. (2021). Resting-state functional connectivity of the human hypothalamus. *Handbook of Clinical Neurology*, *179*, 113–124.

Lips, M. A., Wijngaarden, M. A., van der Grond, J., van Buchem, M. A., de Groot, G. H., Rombouts, S. A., Pijl, H., & Veer, I. M. (2014). Resting-state functional connectivity of brain regions involved in cognitive control, motivation, and reward is enhanced in obese females. *The American Journal of Clinical Nutrition*, *100*, 524–531.

Lowe, C. J., Reichelt, A. C., & Hall, P. A. (2019). The prefrontal cortex and obesity: A health neuroscience perspective. *Trends in Cognitive Sciences*, *23*, 349–361.

Lynch, L. K., Lu, K. H., Wen, H., Zhang, Y., Saykin, A. J., & Liu, Z. (2018). Task-evoked functional connectivity does not explain functional connectivity differences between rest and task conditions. *Human Brain Mapping*, *39*, 4939–4948.

Maldjian, J. A., Laurienti, P. J., Kraft, R. A., & Burdette, J. H. (2003). An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. *NeuroImage*, *19*, 1233–1239.

McLaren, D. G., Ries, M. L., Xu, G., Johnson, S. C., (2012). A generalized form ofcontext-dependent psychophysiological interactions (gPPI): a comparison tostandard approaches. *Neuroimage*, 61, 1277–1286

Mehl, N., Morys, F., Villringer, A., & Horstmann, A. (2019). Unhealthy yet avoidable-how cognitive bias modification alters behavioral and brain responses to food cues in individuals with obesity. *Nutrients*, *11*, 874.

Mehta, S., Melhorn, S. J., Smeraglio, A., Tyagi, V., Grabowski, T., Schwartz, M. W., & Schur, E. A. (2012). Regional brain response to visual food cues is a marker of satiety that predicts food choice. *The American Journal of Clinical Nutrition*, *96*, 989–999.

Morys, F., Garcia-Garcia, I., & Dagher, A. (2020). Is obesity related to enhanced neural reactivity to visual food cues? A review and meta-analysis. *Social Cognitive and Affective Neuroscience*, *nsaa113*. Advance online publication. https://doi.org/10.1093/scan/nsaa113

Neseliler, S., Han, J. E., & Dagher, A. (2017). The use of functional magnetic resonance imaging in the study of appetite and obesity. In R. B. S. Harris (Ed.), *Appetite and food intake: Central control* (pp. 117–134). CRC Press.

Neudorfer, C., Germann, J., Elias, G. J. B., Gramer, R., Boutet, A., & Lozano, A. M. (2020). A high-resolution in vivo magnetic resonance imaging atlas of the human hypothalamic region. *Scientific Data*, *7*, 305.

Nieuwenhuys, R., Voogd, J., & Huijzen, C. (2008). *The human central nervous system. A synopsis and atlas* (4th ed.). Steinkopff Heidelberg.

Page, K. A., Chan, O., Arora, J., Belfort-Deaguiar, R., Dzuira, J., Roehmholdt, B., Cline, G. W., Naik, S., Sinha, R., Constable, R. T., & Sherwin, R. S. (2013). Effects of fructose vs glucose on regional cerebral blood flow in brain regions involved with appetite and reward pathways. *JAMA*, *309*, 63–70.

Pursey, K. M., Stanwell, P., Callister, R. J., Brain, K., Collins, C. E., & Burrows, T. L. (2014). Neural responses to visual food cues according to weight status: A systematic review of functional magnetic resonance imaging studies. *Frontiers in Nutrition*, *1*, 7.

Rolls, E. T., Huang, C.-C., Lin, C.-P., Feng, J., & Joliot, M. (2020). Automated anatomical labelling atlas 3. *NeuroImage*, *206*, 116189. https://doi.org/10.1016/j.neuroimage.2019.116189

Sewaybricker, L. E., Melhorn, S. J., Askren, M. K., Webb, M. F., Tyagi, V., De Leon, M. R. B., Grabowski, T. J., Seeley, W. W., & Schur, E. A. (2020). Salience network connectivity is reduced by a meal and influenced by genetic background and hypothalamic gliosis. *International Journal of Obesity*, *44*, 167–177.

Siep, N., Roefs, A., Roebroeck, A., Havermans, R., Bonte, M. L., & Jansen, A. (2009). Hunger is the best spice: An fMRI study of the effects of attention, hunger and calorie content on food reward processing in the amygdala and orbitofrontal cortex. *Behavioural Brain Research*, *198*, 149–158.

Smeets, P. A. M., Dagher, A., Hare, T. A., Kullmann, S., van der Laan, L. N., Poldrack, R. A., Preissl, H., Small, D., Stice, E., & Veldhuizen, M. G. (2019). Good practice in food-related neuroimaging. *The American Journal of Clinical Nutrition*, *109*, 491–503.

Stice, E., Spoor, S., Bohon, C., Veldhuizen, M. G., & Small, D. M. (2008). Relation of reward from food intake and anticipated food intake to obesity: A functional magnetic resonance imaging study. *Journal of Abnormal Psychology*, *117*, 924–935.

Stice, E., & Yokum, S. (2018). Relation of neural response to palatable food tastes and images to future weight gain: Using bootstrap sampling to examine replicability of neuroimaging findings. *NeuroImage*, *183*, 522–531.

Syan, S. K., McIntyre-Wood, C., Minuzzi, L., Hall, G., McCabe, R. E., & MacKillop, J. (2021). Dysregulated resting state functional connectivity and obesity: A systematic review. *Neuroscience and Biobehavioral Reviews*, *131*, 270–292.

Tiedemann, L. J., Schmid, S. M., Hettel, J., Giesen, K., Francke, P., Buchel, C., & Brassen, S. (2017). Central insulin modulates food valuation via mesolimbic pathways. *Nature Communications*, *8*, 16052.

Uher, R., Treasure, J., Heining, M., Brammer, M. J., & Campbell, I. C. (2006). Cerebral processing of food-related stimuli: Effects of fasting and gender. *Behavioural Brain Research*, *169*, 111–119.

van Strien, T., Frijters, J. E. R., Bergers, G. P. A., Defares, P. B. (1986). The Dutch EatingBehavior Questionnaire (DEBQ) for assessment of restrained, emotional, and external eating behavior. *International Journal of Eating Disorders*, *5*, 295–315

van der Laan, L. N., de Ridder, D. T., Viergever, M. A., & Smeets, P. A. (2011). The first taste is always with the eyes: A meta-analysis on the neural correlates of processing visual food cues. *NeuroImage*, *55*, 296–303.

van Meer, F., van der Laan, L. N., Eiben, G., Lissner, L., Wolters, M., Rach, S., Herrmann, M., Erhard, P., Molnar, D., Orsi, G., Viergever, M. A., Adan, R. A. H., Smeets, P. A. M., & Consortium, I. F. (2019). Development and body mass inversely affect children's brain activation in dorsolateral prefrontal cortex during food choice. *NeuroImage*, *201*, 116016.

van Meer, F., van der Laan, L. N., Viergever, M. A., Adan, R. A. H., Smeets, P. A. M., & I.Family Consortium. (2017). Considering healthiness promotes healthier choices but modulates medial prefrontal cortex differently in children compared with adults. *NeuroImage*, *159*, 325–333.

Veit, R., Horstman, L. I., Hege, M. A., Heni, M., Rogers, P. J., Brunstrom, J. M., Fritsche, A., Preissl, H., & Kullmann, S. (2020). Health, pleasure, and fullness: Changing mindset affects brain responses and portion size selection in adults with overweight and obesity. *International Journal of Obesity*, *44*, 428–437.

Veit, R., Schag, K., Schopf, E., Borutta, M., Kreutzer, J., Ehlis, A. C., Zipfel, S., Giel, K. E., Preissl, H., & Kullmann, S. (2021). Diminished prefrontal cortex activation in patients with binge eating disorder associates with trait impulsivity and improves after impulsivity-focused treatment based on a randomized controlled IMPULS trial. *NeuroImage: Clinical*, *30*, 102679.

Wever, M. C. M., van Meer, F., Charbonnier, L., Crabtree, D. R., Buosi, W., Giannopoulou, A., Androutsos, O., Johnstone, A. M., Manios, Y., Meek, C. L., Holst, J. J., Smeets, P. A. M., & Full4Health Consortium. (2021). Associations between ghrelin and leptin and neural food cue reactivity in a fasted and sated state. *NeuroImage*, *240*, 118374.

Wijngaarden, M. A., Veer, I. M., Rombouts, S. A., van Buchem, M. A., Willems van Dijk, K., Pijl, H., & van der Grond, J. (2015). Obesity is marked by distinct functional connectivity in brain networks involved in food reward and salience. *Behavioural Brain Research*, *287*, 127–134.

Wright, H., Li, X., Fallon, N. B., Crookall, R., Giesbrecht, T., Thomas, A., Halford, J. C., Harrold, J., & Stancak, A. (2016). Differential effects of hunger and satiety on insular cortex and hypothalamic functional connectivity. *The European Journal of Neuroscience*, *43*, 1181–1189.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Kullmann, S., Veit, R., Crabtree, D. R., Buosi, W., Androutsos, O., Johnstone, A. M., Manios, Y., Preissl, H., & Smeets, P. A. M. (2023). The effect of hunger state on hypothalamic functional connectivity in response to food cues. *Human Brain Mapping*, *44*(2), 418–428. https://doi.org/10.1002/hbm.26059