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Sex/Gender Differences in Neural Correlates of Food Stimuli: A Systematic Review of Functional Neuroimaging Studies

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Abstract

Sex and gender differences in food perceptions and eating behaviors have been reported in psychological and behavioral studies. The aim of this systematic review was to synthesize studies that examined sex/gender differences in neural correlates of food stimuli, as assessed by functional neuroimaging. Published studies to 2016 were retrieved and included if they used food or eating stimuli, assessed patients with functional magnetic resonance imaging (fMRI) or positron emission tomography (PET), and compared activation between males and females. Fifteen studies were identified. In response to visual food cues, females, compared to males, showed increased activation in the frontal, limbic, and striatal areas of the brain as well as the fusiform gyrus. Differences in neural response to gustatory stimuli were inconsistent. This body of literature suggests that females may be more reactive to visual food stimuli. However, findings are based on a small number of studies and additional research is needed to establish a more definitive explanation and conclusion.

Keywords

Sex; gender; obesity; neuroimaging

Overweight and obesity are more prevalent in females than males. In the United States, 35.0% of males are obese, compared to 40.4% of females.¹ The prevalence of class III obesity is 9.9% among females, compared to 5.5% among males.¹ At the same time, eating disorders are three times more common in females.² Additionally, males and females often

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differ in their food preferences and eating behaviors. Males report diets with higher energy density.³ Females, in comparison to males, report greater consumption of fruits, vegetables, and fiber.^{4–6} While females prefer more snack-related comfort foods such as candy and chocolate, males favor more meal-related foods such as pizza, pasta, steak, and beef.⁷ Females have higher food cravings for sweet foods, while males have higher food cravings for savory foods.⁸ Males and females also differ in eating styles. Males take bigger bites of food and eat at a faster rate compared to females.⁹ Cognitive dietary restraint and disinhibition are higher among females than males.¹⁰ Foods and eating styles can be thought of as gendered: healthy and small meals are associated with femininity, and unhealthy and large meals are associated with masculinity.¹¹ As such, packaging for healthier foods such as salad and yogurt are more frequently adorned with stereotypically feminine fonts and color choices, whereas unhealthy and heavier foods, such as beef and beer, are often in more stereotypically masculine packaging.¹²

Differences in food preferences and eating behaviors may be related to biological “sex” and/or psycho-social-cultural “gender.”¹³ Sex is the classification, typically as male or female, according to the reproductive organs and functions that derive from the chromosomal complement.¹⁴ Gender is an individual’s self-representation as male or female, or how that person is responded to by social institutions on the basis of the person’s gender presentation.¹⁴ Conceptually, sex and gender are distinct. However, the practical challenges of separating biological versus social causes of differences between males and females have been highlighted by a number of authors.^{15–17} We use the term “sex/gender” in this paper to reflect this overlap. Recent advances in neuroimaging have allowed scientists to investigate factors, such as sex/gender, which influence neural responses to food stimuli.

Several reviews have synthesized results from functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) studies examining neural responses to food stimuli.^{18–24} These reviews have demonstrated core homeostatic and hedonic neural mechanisms underlying eating behaviors and food choices including the limbic, striatal and frontal neural circuitries. The importance of internal and external modulating factors such as fasting or fed state,²² weight status,^{19,20,24} eating-related pathology,²³ and energy density^{21,25} have also been highlighted in these reviews. Despite evidence of behavioral and psychological sex/gender variances in eating behaviors and food choices, to date, no systematic reviews have examined differences in neural responses to food perceptions and eating behaviors between males and females. The purpose of this review was to synthesize results from fMRI and PET studies that have investigated sex/gender differences in neural correlates of food stimuli.

Methods

Literature Search and Study Selection

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).²⁶ The following electronic databases were searched: PubMed, EMBASE, Scopus, and the Cochrane Library. A pre-determined list of keyword search terms was informed and compiled from a preliminary search of the literature and expanded medical subject headings (MeSH). Keywords included combinations of the following: (i)

fMRI, “functional magnetic resonance,” blood oxygen level dependent (*BOLD*), functional imaging, *BOLD* signal, *BOLD* effect, oxyhemoglobin, and deoxyhemoglobin, neuroimaging, *PET*, positron emission tomography; (ii) gender, sex; and (iii) food, eat*. Electronic searches were supplemented by systematically checking reference lists of relevant publications.

The search yielded 429 studies, excluding duplicates. Two authors (AMC and either CMH or ZMB) independently screened all article titles. Any non-English or clearly irrelevant entries were excluded. Next, the remaining abstracts were reviewed to identify studies for full text review. The *a priori* eligibility criteria for articles were that they: (i) were peer-reviewed original research articles in English language journals; (ii) examined human participants; (iii) were published between the inception of the database and June 2016; (iv) used *fMRI* or *PET*; (v) used scans to examine food stimuli; and (vi) reported contrasts between males and females. Studies that simply reported separate results for males and females, without directly statistically assessing the observed differences were not reviewed because of the interpretive limitations associated with such reports. Searches were conducted with the consultation of a research librarian. Inter-reviewer agreement was assessed using a simple kappa statistic. Disagreement was resolved by consensus. Please see Figure 1 for a schematic depiction of our article selection process.

Data extraction and synthesis—Data from each article were extracted independently by two authors (AMC and either CMH or ZMB) using a standardized tool that contained sections for study characteristics (Table 1), study results (Table 2), and study quality (Table 3). Quality was assessed using 11 criteria that were adapted from a previous systematic, neuroimaging review.²⁷ The criteria were: clear research objective; clear recruitment procedure; adequate description of inclusion/exclusion criteria; report on sample demographics; participation rates; sufficient assessment of food stimuli measurements; imaging protocol; reporting of strength of effect; use of appropriate statistical analysis; acknowledgement of study limitations; and participation rate >70%. Due to the limited number of studies, all studies were included regardless of quality. Study findings were only extracted on results that reached thresholds for statistical significance that were stipulated by the study authors *a priori*. Disagreements were resolved through consensus. Due to heterogeneity, data were integrated using a qualitative synthesis process.

Results

Study Selection

Based on the literature search strategies, 429 unique citations were retrieved from the databases. Among these, 12 reports met inclusion criteria. Three additional studies were found from review of reference lists, for a total of 15 article included in this review (Figure 1). The inter-reviewer agreement ($Kappa=0.97$) indicated excellent agreement among reviewers.

Participant Characteristics

The number of participants per study ranged from 12 to 49 (Table 1). Eleven of the studies were conducted in the US. Across trials, the average body mass index (BMI) ranged from 21.3 to 36.9 kg/m² for females and from 21.5 to 36.2 kg/m² for males. Two studies only included participants who were obese (BMI ≥ 30 kg/m²), two included individuals with a BMI < 35 kg/m², four included participants with BMIs < 30 kg/m², and two included participants with BMIs < 25 kg/m². The five remaining studies did not report the specific BMI range of participants. The mean age in each study was between 15.6 to 48.0 years. The percent of female participants ranged from 37.2% to 57.1%. Five studies explicitly stated that all females were premenopausal. However, all studies included participants 48 years and under, and participants who were considered healthy (i.e., free of significant medical conditions or psychiatric history).

Study Designs

Two studies used PET, and the remainder employed fMRI (Table 2). Eight studies examined sex/gender as a primary outcome/hypothesis. The seven remaining studies explored sex/gender differences as a secondary aim. The studies included a number of stimuli to provoke neural responses; seven employed visual stimuli, four used gustatory stimuli, three had multiple stimuli, and one used auditory stimuli. Six studies were conducted with participants fasting only, one fed only, seven both fasted and fed, and one did not report whether participants were fasted or fed. Three studies standardized for menstrual cycle phase among female participants (all conducted during the follicular phase), and one study controlled for menstrual phase. Table 2 lists the thresholds for all studies that included a whole-brain analysis.

Study Results

Visual cues: Fasted—Nine studies included responses to visual stimuli of food cues during a fasted state.^{28–36} Food pictures were described as high or low “calorie,” “energy dense,” or “hedonic” (Table 2). Herwig et al. (2016) compared foods based on individuals’ ratings of foods as healthy or unhealthy.³⁴ Eight studies used functional localization techniques (i.e., analyses that assume specific mental functions are localized to specific brain regions³⁷). One study used a functional connectivity analysis to examine the integration of different regions of the brain in association with visual food cue processing.³²

Four of the nine studies directly compared neural responses to visual pictures of high- and low-calorie foods.^{28,31,33,35} Compared to males, females demonstrated greater activation in regions of the prefrontal cortex including the lateral prefrontal cortex,²⁸ dorsolateral prefrontal cortex,²⁸ middle frontal gyrus³¹, inferior lateral orbitofrontal cortex,³¹ and ventromedial/orbitofrontal cortex³¹ (Table 2). Females, relative to males, also showed more activation in areas of the limbic and striatal systems (middle/posterior cingulate gyrus³¹ and caudate nucleus³⁵), as well as, the insular cortices,³¹ parietal cortex,²⁸ fusiform gyrus,^{28,33} and temporal-occipital area.³⁵ Two studies found no regions more activated in males compared to females.^{28,33} In one of the smaller studies (N=16), males, compared to females, had greater activation in the amygdala.³¹ In another study, males who were obese had greater activation in the inferior parietal lobe compared to females who were obese.³⁵

The remaining four studies utilized other study paradigms. Compared to females, males had higher activity in the ventral striatum when evaluating unhealthy stimuli.³⁴ Activation in the midbrain was higher among females when rating healthy stimuli compared to unhealthy stimuli.³⁴ Atalayer et al. (2014) examined sex/gender differences among participants who were obese using a functional connectivity analysis of two seed regions—the amygdala and the ventral striatum.³² In both seed regions, males had greater functional connectivity with the supplementary frontal motor area, precentral gyri, cuneus, and precuneus. Compared to males, females showed greater functional connectivity with the amygdala and thalamus, inferior frontal gyrus, and dorsomedial prefrontal cortex.

Two studies correlated neural responses to visual food stimuli with behaviors. Killgore et al. (2013a) examined neural responses to high- and low-calorie food stimuli in relation to appetite and urge to overeat.²⁹ Among females, reduced responsiveness of the prefrontal cortex to food images was associated with a greater urge to overeat. In another study, Killgore et al. (2013b) examined whether responsiveness to high- and low-calorie pictures was associated with BMI.³⁰ The combined cluster activation response in reward regions (i.e., amygdala, insula, and orbitofrontal cortex) was predictive of BMI for females, accounting for 75.6% of the variance in body mass. There was no significant association for males.

Visual cues: Fed—Four studies examined responses to visual stimuli after being fed.^{32,33,35,36} When viewing pictures of high-energy-density foods, males, compared to females, showed greater activation in the fusiform gyrus.³⁵ Females showed greater activation in the anterior cingulate cortex relative to males.³⁵ Atalayer et al. (2014) found that males who were obese, compared to females who were obese, had greater functional connectivity with the amygdala and subgenual anterior cingulate.³² Females, relative to males, had greater functional connectivity between the amygdala and angular gyrus and precentral gyrus.³² No regions were significant when the ventral striatum was used as the seed region. In a small study (N=12), Frank et al. (2010) compared differences in neural activation from a fasted to fed state.³⁶ While viewing high-calorie foods, females, relative to males, had decreased activation in the superior medial frontal lobe, fusiform gyrus, anterior cingulate cortex as well as the olfactory and middle frontal lobe.³⁶

Gustatory cues—Six studies examined gustatory cues during scans,^{33,38–42} and two of these studies used PET.^{41,42} Five studies included sweet tastes or flavors (i.e., two used sucrose, two tested chocolate milk, one administered Ensure; Table 2). When fasted, males, relative to females, had greater activation in the dorsolateral prefrontal cortex, middle temporal gyrus, posterior cingulate, and parahippocampal gyrus.⁴² When fed, females had greater response than males in the dorsolateral prefrontal cortex, precuneus, angular gyrus, and occipital-temporal cortex.⁴² After being fed, males had greater activation in the ventromedial prefrontal cortex⁴² and caudate compared to females.³⁸ Haase et al. (2011) found no differences in neural response to sucrose between males and females when fasted.³⁹ Three studies examined variations between males and females in sweet taste from fasting to fed states.^{39,40,42} Smeets et al. (2006) found that relative to males, females had greater decreases in activation in the hypothalamus after being satiated.⁴⁰ Del Parigi et al. (2002) demonstrated that in response to satiation, females had greater cerebral blood flow in

the dorsolateral prefrontal cortex, precuneus, angular gyrus, occipital-temporal cortex, compared to males.⁴² Males had increased activation after satiation in the ventral striatum³⁷ and ventromedial prefrontal cortex³⁹ and decreased activation from hunger to satiety in the medial frontal gyrus,⁴⁰ insula, inferior frontal gyrus, cerebellum, parahippocampal gyrus, anterior cingulate, caudate, lentiform nucleus, posterior cingulate, fusiform gyrus, middle and superior temporal gyri, lingual gyrus, cuneus, amygdala, uncus, and precentral gyrus.³⁹ Uher et al. (2006) showed that irrespective of being fasted or fed, females showed stronger responses to sweet taste in the anterior insula, frontal operculum, and medial apical prefrontal cortex.³³ In addition to sweet taste, Haase et al. (2011) also tested bitter (caffeine), sour (citric acid), and salty (sodium chloride) tastes.³⁹ There were differences in activation patterns based on the types of taste, condition (fasted vs fed) and sex/gender (Table 2).³⁹

In a study by Wang et al. (2009), participants were scanned 3 times: once after they observed and spontaneously reacted to their favorite foods; once when instructed to inhibit their desire for food before the presentation of the food stimuli; and once without stimulation.⁴¹ In food stimulation with cognitive inhibition, males had greater decreases than females in the amygdala, striatum, orbitofrontal cortex, parahippocampus, hippocampus, hypothalamus and cerebellum.

Auditory cues—Two studies used auditory stimuli.^{35,43} In a study from Geliebter et al. (2013), neural responses to short auditory descriptions of high-energy-density foods were compared to low-energy-density foods.³⁵ When fasted, females demonstrated greater activation than males in the right parahippocampal gyrus. Males did not show greater neural activation in any regions compared to females when fasted. When fed, males, compared to females, showed greater activation in the bilateral supplementary motor areas and precentral gyrus. Females did not show greater activation in any regions when fed versus males. Hommer et al. (2013) conducted a study with adolescents assessing neural responses to script-driven imagery of favorite foods.⁴³ During descriptions of the foods, males had greater activation in the superior, middle, medial frontal gyri and bilateral parietal lobes, compared to females.

Quality Assessment

The mean quality score was 6.4 out of 11 possible points (Table 3). The range of scores was from 4 to 8. No study fulfilled all quality score criteria. Nine studies fulfilled 7 or more of the criteria.

Discussion

This is the first systematic review to investigate sex/gender differences in neural responses to food stimuli. There was support of group-level differences between males and females in neural activation to visual, gustatory, and auditory food stimuli across studies, though activation patterns varied and results should be interpreted cautiously given the limited literature available. Three primary central nervous systems control eating processes.¹⁹ The first is the hypothalamic system that responds to homeostatic mechanisms, through which food intake is balanced with energy requirements. Second is the striatal/limbic system which controls emotion/memory and current and past reward experiences, including food

motivation. The third is the frontal and cortical system that allows pursuit of more abstract goals, reasoning, and executive functioning.^{19,44} In the current review, there was fairly consistent evidence that females, relative to males, had higher neural activation when viewing food stimuli in the latter two systems.

Among females, overeating in response to food cues within the environment is associated with weight gain.⁴⁵ Consistent with this behavioral finding, while cognitively inhibiting food intake, females did not show a significant suppression of regional brain metabolism in the limbic areas of the brain associated with emotional regulation, interoception, and conditioning.³⁸ Neural responses to food stimuli in areas of the brain associated with reward, interoception, cravings for substances, and decision making (i.e., amygdala, insula, and orbitofrontal cortex) were also related to overeating and BMI among females but not males.^{29,30,46–48} Taken together, this suggests that females may have greater difficulties deactivating these areas of the brain to overcome the motivational drive to eat.

Weight status may have influenced study findings and may moderate the relationships between neural responsiveness to food stimuli. While most studies demonstrated that females were more reactive to visual to food stimuli compared to males, 4 of the 9 studies showed areas of the brain that were more reactive among males relative to females. Two of these studies were from samples of patients who were obese.³⁵ In another study that found that males had greater reactivity than females, the mean BMI for males was 27.1 kg/m², compared to a mean BMI of 23.5 kg/m² for females.³¹ It is possible that as BMI increases, differences between males and females may become attenuated.

Consistent with other reviews,^{19–25} we found that a variety of factors moderated sex/gender differences in responses to food stimuli including state (fasted vs fed) and stimuli type. Relative to results from studies examining visual food stimuli, responses to gustatory stimuli were mixed. Cornier et al. (2015) and Smeets et al. (2006) found that males, compared to females, had greater responses to sweet taste in the caudate nucleus and ventral striatum, which are associated with reward salience and incentive motivation.⁴⁹ However, other studies found that females had greater neural responses compared to males. Uher et al. (2006) showed that in response to chocolate milk and chicken broth, females had greater activation in the anterior insula, frontal operculum, and prefrontal cortex. Hasse et al. (2011) found that during satiation, females showed greater activation within the posterior cingulate in response to sweet taste. These areas of the brain are associated with interoception, emotional awareness, planning, and decision making.⁵⁰ While these results suggest that there may be sex/gender-specific neural responses to gustatory stimuli, further investigation is needed to clarify these inconsistencies.

The mechanisms underlying the differences in response to food stimuli between males and females remain elusive but are likely a result of complex physiological (i.e., sex-related) and/or psycho-sociocultural (i.e., gender-related) factors. Socialization to different eating behaviors occurs at a young age,⁵¹ and up to 50% of sex/gender differences in food choice can be attributable to health beliefs and weight control motivation.^{4,52} Thus, differences between males and females on neural response could be due to variations in cognitive or emotional processes as a result of being socialized to consume certain types of foods. Since

neural circuitry is plastic and develops through and is altered by experiences,⁵³ it is possible that sex/gender effects on neural functioning and behavior are a result of gendered life experiences and social constructions. Additional research is needed to examine whether sociocultural factors may account for differences.⁵⁴

Preclinical and clinical studies have demonstrated that feeding behaviors are, in part, mediated by gonadal hormones such as estrogens. These hormones may produce organizational effects (i.e., permanent consequences related to hormonal exposure during early development) and/or activational effects (i.e., ongoing hormonal signaling during other life stages), due to direct effects on the central nervous system or indirect effects through effects on orexigenic and anorexigenic neuropeptides (e.g., ghrelin, insulin, leptin).^{55,56} In rats, bilateral ovariectomy produces rapid increases in food intake and weight gain, but these responses are normalized by estradiol treatment.⁵⁷ In humans, estrogen phasically inhibits food intake. Food intake is 190 kcals/day less during the follicular/peri-ovulatory phase of the cycle than in the luteal and menstrual phases. The nadir occurs around the time of ovulation, when circulating estrogen levels peak.⁵⁸ These cyclical changes in food intake are not seen until puberty.⁵⁹ Females who have anovulatory menstrual cycles do not demonstrate these cyclical changes in food intake.⁶⁰ Neuroimaging results also support the effect of menstrual cycle hormones on response to food stimuli. Results suggest that neural response to food cues in areas such as the amygdala, nucleus accumbens, and fusiform gyrus are greater during the late follicular phase (when estradiol is high) compared to the early follicular and luteal phases.^{61,62} Only four studies in this review accounted for menstrual phase. Given these within-person changes in ovarian hormones, neurological responses may have been enhanced or disguised. Further evaluation of neural function and relationships with hormonal factors over the course of the menstrual cycle is critical to understanding sex differences in food perceptions and eating behaviors. Longitudinal data are needed to examine whether adult sex differences are a result of organizational and/or activational effects.

Studies are needed to clarify the extent to which mechanisms related to sex, gender and their intersection underlie these findings. Examining differences between males and females is complex and requires consideration of different dimensions and measures of sex/gender including structural (e.g., cultural gender norms), social (e.g., social context and role), and individual level-factors (e.g., gender identity, hormones).⁶³ In particular, studies that are well-powered with *a priori* comparisons of biological, social and biosocial mechanisms will help to advance our understanding of differences between males and females in eating behaviors and food choices.¹⁶

There are several limitations to this review and gaps in the literature. First, there were a limited number of articles that compared sex/gender differences, and sample sizes in each study were small. The heterogeneity of study variables and paradigms made direct comparisons between studies challenging. All studies included patients who were healthy and free of major medical and psychiatric conditions, and only one study reported the race/ethnicity of participants. Additionally, independent replication of these fMRI studies is necessary. Seven of the fifteen studies included sex/gender analyses as secondary analyses. This is a concern as most studies did not control for variables such as menstrual cycle phase

or status and hormonal contraceptive use. Results based on a small number of participants, whole-brain analyses that used uncorrected thresholds, and region of interest analyses were also included in this review. This may have resulted in studies being underpowered to detect true differences while also increasing the risk for false positives.^{64,65} While studies reported statistical significance values, better reporting of effect sizes is needed to fully evaluate how substantial differences are between males and females. Thus, generalizability is limited and results should be interpreted cautiously. Findings require replication before they can be assumed to be reliable. Additionally, non-English publications were omitted. As noted in other reviews examining sex/gender differences in neural outcomes,³⁰ publication bias, false-positive errors, and search strategies likely biased the findings towards data with significant results. Clear interpretation of study findings is limited and future studies would benefit from collection of objective and subjective data about food perceptions and eating behaviors.

Functionally, it appears that females and males differ in neural responses to food cues in the frontal, limbic, and striatal areas of the brain as well as the fusiform gyrus, particularly to visual food cues while fasted. Compared to males, females may be more sensitive or reactive to visual food cues, suggesting more cognitive processing related to executive functioning, emotion and reward when viewing food stimuli. This conclusion is based on a limited number of studies with small sample sizes thus caution is needed when interpreting results. Also, relating neural activation to functional significance is based on reverse inference and should be considered speculative.^{66,67} Further research is needed on differences and similarities between males and females as this could have implications for the development of relevant sex/gender-informed prevention and treatment options for obesity and disordered eating. These findings suggest that vulnerabilities to obesity and disordered eating, which are more common among females, may be influenced by greater neurocognitive responsiveness to food stimuli. Further research is also required in larger samples to confirm these findings, including studies that explore differential effects among males and females across weight status.

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Figure 1.
Flow diagram for literature search

Table 1

Participant characteristics in studies included in systematic review

Study	Setting	Total N	Female N	BMI kg/m ²	M±SD	Range	Age years	All females premenopausal	Menstrual cycle phase	Race/ethnicity
Atalayer et al., 2014 [32]	New York, US	31	14	M=36.2±5.5 F=36.9±5.6	30	25–45	M=35.0±9.0 F=35.0±6.9	Yes	NR	NR
Cornier et al., 2010 [28]	Colorado, US	43	22	M=24.2±3.0 F=24.3±4.1	NR	25–45	M=34.2±5.7 F=35.8±5.4	Yes	Follicular	NR
Cornier et al., 2015 [38]	Colorado, US	49	24	M=24.2±3.3 F=22.9±4.1	17–30	25–40	M=30.2±3.3 F=30.4±3.2	Yes	Follicular	NR
Del Parigi et al., 2002 [42]	Arizona, US	44	22	NR	NR	NR	M=31.0±8.0 F=31.0±9.0	Yes	Follicular	NR
Frank et al., 2010 [36]	Tubingen, Germany	12	6	Total= 22.4±2.55	<25	NR	Total=27.4±4.1	NR	NR	NR
Geliebter et al., 2013 [35]	New York, US	31	14	M=36.2±5.5 F=36.9±5.6	30	NR	M=35.0±9.0 F=35.0±6.9	Yes	NR	NR
Haase et al., 2011 [39]	California, US	21	12	M=23.2±3.5 F=22.8±2.6	NR	19–26	M=22.3±2.7 F=21.9±1.9	NR	NR	NR
Hervig et al., 2016 [34]	Zuerich, Switzerland	37	18	M=22.9±2.4 F=21.3±2.1	18.0–28.6	20–46	M=24.8±4.6 F=25.3±5.5	NR	NR	NR
Honner et al., 2013 [43]	Connecticut, US	43	16	NR	NR	14–17	Total= 15.6±0.8	NR	NR	93% African American
Kilgore & Yurgelun-Todd, 2010 [31]	Massachusetts, US	16	8	M=27.1±5.5 F=23.5±4.5	NR	NR	M=46.5±5.4 F=48.0±5.7	NR	NR	NR
Kilgore et al., 2013a [29]	Massachusetts, US	38	16	M=24.2±3.6 F=25.1±4.0	19.8–34.8	18–45	M=31.5±9.3 F=28.3±7.5	NR	NR	NR
Kilgore et al., 2013b [30]	Massachusetts, US	38	16	M=24.2±3.6 F=25.1±4.0	19.8–34.8	18–45	M=31.5±9.3 F=28.3±7.5	NR	Statistical control	NR

Study	Setting	Total N	Female N	BMI kg/m ²	M±SD		Range		Age years	All females premenopausal	Menstrual cycle phase	Race/ethnicity
Smeets et al., 2006 [40]	Utrecht, Netherlands	24	12	M=21.5±1.6 F=22.0±1.4	M=21.5±1.6 F=22.0±1.4	M=21.3±2.8 F=20.5±1.5	19–25	18–28	NR	NR	NR	NR
Uher et al., 2006 [33]	London, UK	18	10	M=22.4±2.5 F=22.5±2.8	M=22.4±2.5 F=22.5±2.8	M=29.4±7.8 F=28.4±8.4	17–27.4	20–44	NR	NR	NR	NR
Wang et al., 2009 [41]	New York, US	23	13	Total= 24.8±2.7	Total= 24.8±2.7	Total=32.6±7.5	20–29	22–48	NR	NR	NR	NR

Note. BMI=body mass index. M=males. F=females. NR=not reported.

Study descriptions and results from investigations of sex/gender differences in neural correlates of food stimuli

Table 2

Study	Type of stimuli contrasted	Imaging modality; Acquisition strength	Nutrition standardization	Analysis (WB Threshold)	Major Inclusion and Exclusion Criteria/Covariates	Male>Female	Female>Male
<i>Multiple stimuli</i>							
Geliebter et al., 2013 [35]	Visual: High vs low energy density foods Auditory: High vs low energy density foods	fMRI; 1.5T	12 hours Liquid meal	WB ($p<0.05$, corrected, Monte Carlo; $k = 147$)	Healthy; right-handed; obese; stable weight $\times 3$ months; non-smokers; no exercise pre scan; premenopausal	Fasted (visual): R B caudate; R temporal-occipital area Fasted (auditory): R parahippocampal gyrus Fed (visual): R dorsal ACC	Fasted (visual): B caudate; R temporal-occipital area Fasted (auditory): R parahippocampal gyrus Fed (visual): R dorsal ACC
Uher et al., 2006 [33]	Visual: Savory and sweet foods vs non-edible objects Taste: Chocolate milk; chicken broth; artificial saliva	fMRI; 1.5T	24 hours Eating as usual	WB ($p<0.005-0.001$, cluster-wise)	Healthy; right-handed; not vegetarian or selective eater	Fed (visual): L fusiform gyrus Fed (auditory): B SMA and R precentral gyrus	Visual: B Fusiform gyrus Tastes (both): L anterior insula; L frontal operculum; B medial apical PFC Tastes (chicken): L anterior insula
Wang et al., 2009 [41]	Individual's favorite food (taste, smell, view)	PET	17–19 hours	ROI; global metabolism	Healthy; no history of eating disorders, surgical/medical treatment for weight control	Food stimulation with and without cognitive inhibition: Greater decreases in L OFC; L uncus; L parahippocampus; B amygdala; R putamen; cerebellar vermis	

Study	Type of stimuli contrasted	Imaging modality; Acquisition strength	Nutrition standardization		Analysis (WB Threshold)	Major Inclusion and Exclusion Criteria/ Covariates	Male>Female	Female>Male
Visual stimuli								
Atalayer et al., 2014 [32]	High vs low energy density	fMRI; 1.5T	Overni ght	Liquid meal	ROI; Functional connectivity	Healthy; right-handed; obese; stable weight $\times$ 3 months; non-smokers; no exercise pre scan; premenopausal	Fasted: Greater functional connectivity with AMG in R SMA; B precentral gyri; R cuneus; L precuneus; greater functional connectivity with VS in the B SMA; R precentral gyrus; L precuneus	Fasted: Greater functional connectivity with AMG in L IFG; R thalamus; R dorsomedial PFC
Comier et al., 2010 [28]	Primary: High hedonic value foods vs neutral-non-food items Secondary: High vs neutral hedonic value foods	fMRI; 3.0T	Overnight		WB (p<0.05, FDR, k= 130); ROI	Healthy; right-handed; follicular phase of menstrual cycle; not actively dieting	Fed: Functional connectivity with AMG in L subgenual anterior cingulate	Fed: Functional connectivity with AMG in L angular gyrus and R precentral gyrus
Frank et al., 2010 [36]	High vs low calorie foods, non-food items	fMRI; 3T	3 hours	After lunch	WB (p<0.05, FDR)	Healthy; right-handed; not dieting	High hedonic vs neutral foods: R parietal cortex; R lateral PFC	High hedonic vs neutral foods: R parietal cortex; R lateral PFC
Hervig et al., 2016 [34]	Individual's ratings of	fMRI; 3T	1 hour		ROI	Healthy; right-handed	R VS in the perception and	Midbrain region associated with

Study	Type of stimuli contrasted	Imaging modality; Acquisition strength	Nutrition standardization		Analysis (WB Threshold)	Major Inclusion and Exclusion Criteria/ Covariates	Male>Female	Female>Male
			Fasted	Fed				
	healthy vs unhealthy foods						evaluation of unhealthy stimuli	rating period of healthy stimuli compared to unhealthy stimuli
Killgore & Yurgelun-Todd, 2010 [31]	High vs low calorie foods, non-food items	fMRI; 3T	1 hour		WB ($p<0.001$, uncorrected, $k=10$); ROI	Healthy	B AMG	L middle frontal gyrus; L inferior lateral OFC; L ventromedial/ OFC; L middle/ posterior cingulate gyrus; B insular cortices
Killgore et al., 2013a [29]	High vs low calorie foods, non-food items	fMRI; 3T	1 hour		ROI	Healthy; right-handed; no recent psychoactive medications or illicit substances		Lower ventromedial PFC associated with eating more than intended
Killgore et al., 2013b [30]	High vs low calorie foods, non-food items	fMRI; 3T	1 hour		ROI	Healthy; right-handed; no recent psychoactive medications or illicit substances; adjusted for menstrual phase		Combined brain responses in B AMG, insula, and medial OFC in response to high calorie foods was associated weight status in females only and accounted for 75.6% of variance in weight status

Gustatory stimuli

Del Parigi et al., 2002 [42]	Hunger vs satiation (liquid meal)	PET	36 hours	Liquid meal	WB ($p<0.005$)	Healthy; right-handed; follicular phase of menstrual cycle; no family history of obesity or diabetes; absence of dietary restraint; sedentary activity only during study	Fasted: Dorsolateral PFC; middle temporal gyrus; posterior cingulate; parahippocampal gyrus Fed: vmPFC	Fed: Dorsolateral PFC; precuneus; angular gyrus;
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Study	Type of stimuli contrasted	Imaging modality; Acquisition strength	Nutrition standardization		Analysis (WB Threshold)	Major Inclusion and Exclusion Criteria/ Covariates	Male>Female	Female>Male
			Fasted	Fed				
Comier et al., 2015 [38]	Sucrose vs artificial saliva with unique paired cue (geometric shape)	fMRI; 3T		Liquid meal	WB (p<0.001, uncorrected, k 10); ROI	Healthy; right-handed; follicular phase of menstrual cycle	Sucrose receipt: R caudate	occipital-temporal cortex
Haase et al., 2011 [39]	Salty (sodium chloride), sour (citric acid), bitter (caffeine), sweet (sucrose)	fMRI; 3T	12 hours	Liquid meal	WB (p 0.005, cluster p<0.05, k 12)	Healthy	<p>Fasted to fed: Global Caffeine, NaCl, citric acid, sucrose: B insula (L only for NaCl); B IFG (L only for NaCl); L cerebellum (B for caffeine) Caffeine, NaCl, sucrose: R parahippocampal gyrus (B for NaCl); R anterior cingulate (B for caffeine) Caffeine, citric acid, sucrose: B IFG (R only sucrose) Caffeine, sucrose: B caudate; R lentiform nucleus; B posterior cingulate (L only for NaCl); B fusiform gyrus (L only for sucrose); B middle and superior temporal gyri; B lingual gyrus and B cuneus NaCl and sucrose: R amygdala; R uncus; R precentral gyrus</p> <p>Fasted: Citric acid; L insula; L thalamus; L parahippocampal gyrus; L lentiform nucleus; R nucleus; R posterior cingulate; R precuneus; L superior temporal gyri; R middle temporal gyri; R postcentral gyrus; cerebellum NaCl: L IFG; R precuneus Fed: Sucrose, caffeine: R Posterior cingulate Citric acid: L Posterior cingulate Sucrose, citric acid: Cerebellum Sucrose, caffeine: R cuneus; R lingual gyrus Citric acid: B thalamus Caffeine: R insula; R IFG; R lentiform nucleus; middle temporal gyrus Fasted to fed: Caffeine: B anterior</p>	

Study	Type of stimuli contrasted	Imaging modality; Acquisition strength	Fasted	Fed	Nutrition standardization	Analysis (WB Threshold)	Major Inclusion and Exclusion Criteria/ Covariates	Male>Female	Female>Male
Smeets et al., 2006 [40]	Chocolate milk	fMRI; 1.5T	Overnight	Chocolate until satiated	WB (p<0.005, k=20); ROI	Healthy; normal weight; no history of alcohol consumption >28 units/wk; no irregular eating habits, dieting or restrained eating	Increased activation after satiation: L VS	Decreased activation after satiation: R medial frontal gyrus	cingulate; B cerebellum
									NaCl: L middle temporal gyrus; L fusiform gyrus; L IFG; L insula Citric acid: L superior temporal gyrus; B insula; L parahippocampal gyrus; R angular gyrus; B middle frontal gyrus; B IFG
Auditory stimuli									
Hommer et al., 2013 [43]	Individualized stress, favorite food and neutral scripts	fMRI; 3T	NR	NR		WB (p<0.05, FWE)	Healthy	Superior, middle, medial frontal gyri; B parietal lobes	

Notes. fMRI=Functional magnetic resonance imaging. PET=positron emission tomography. ROI=region of interest. WB=Whole brain. R=right. L=left. B=bilateral. AMG=amygdala. SMA=supplementary motor area. VS=ventral striatum. IFG=inferior frontal gyrus. PFC=prefrontal cortex. ACC=anterior cingulate cortex. vmPFC=ventromedial prefrontal cortex.

Table 3

Quality assessment scores for included studies

Study	Research objective	Recruitment procedure	Inclusion/exclusion criteria	Sample demographic	Participation rates	Participant rating of food stimuli	Imaging protocol	Strength of effect	Appropriate analysis	Limitations discussed	Participation over 70%	Total Score (Out of 11)
Atalayer et al., 2014 [32]	Yes	Yes	Yes	No	NR	No	Yes	No	Yes	Yes	NR	6
Cornier et al., 2010 [28]	Yes	No	Yes	No	NR	No	Yes	No	Yes	No	NR	4
Cornier et al., 2015 [38]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Del Parigi et al., 2002 [42]	Yes	Yes	Yes	No	NR	No	Yes	No	Yes	Yes	NR	6
Frank et al., 2010 [36]	Yes	No	No	No	NR	No	Yes	No	Yes	Yes	NR	4
Geliebter et al., 2013 [35]	Yes	Yes	Yes	No	NR	No	Yes	No	Yes	Yes	NR	6
Haase et al., 2011 [39]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Herwig et al., 2016 [34]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Honnner et al., 2013 [43]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Kilgore & Yurgelun-Todd, 2010 [31]	Yes	Yes	Yes	No	NR	No	Yes	No	Yes	Yes	NR	6
Kilgore et al., 2013a [29]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Kilgore et al., 2013b [30]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Smeets et al., 2006 [40]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Uher et al., 2006 [33]	Yes	Yes	Yes	No	NR	Yes	Yes	No	Yes	Yes	NR	7
Wang et al., 2009 [41]	Yes	Yes	Yes	No	NR	Yes	Yes	Yes	Yes	Yes	NR	8

Note. NR=not reported and score of 0 is given. For each “yes”, 1 point is given.