Review

Neural correlates of individual differences related to appetite

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ABSTRACT

Using neuroimaging technologies to compare normal weight and obese individuals can reveal much about the pathophysiological state of obesity but such comparisons tell us little about what makes some normal weight individuals susceptible to obesity or about important individual differences amongst obese individuals. The current review therefore reviews neuroimaging research on individual difference measures that can illuminate these important topics. After introducing three neuropsychological models of the nature of motivation to approach rewarding stimuli, neuroimaging research on measures of impulsivity, craving, binge eating, restrained eating and disinhibited eating is reviewed. Although neuroimaging research on individual differences measures of brain activity related to appetite is in its infancy, existing studies suggest that such research could enrich the understanding, prevention and treatment of disordered eating and obesity.

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1. Introduction

As neuroimaging technologies, such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), and electroencephalography (EEG), have become more readily available, researchers have produced an upsurge of studies comparing the brain responses of normal weight and obese individuals to a variety of stimuli and physiological states. These new technologies have great potential to supplement existing literature on behavioral differences between individuals within these weight categories. An illustration of the potential of neuroimaging to clarify behavioral studies can be found in literature comparing obese and normal weight individuals on measures of appetite and food intake. There have been hundreds of behavioral studies comparing normal weight and overweight individuals on these variables during the past 40 years, but these studies have often produced conflicting and contradictory results [1,2]. Neuroimaging research that has compared brain regions associated with eating behavior in obese and normal weight individuals, by contrast, has shown much more consistent differences between these groups [3]. The fact that there is more consistency in

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findings in neuroimaging compared to behavioral studies suggests that investigating the reasons for this difference will yield valuable insights into both neurophysiological and behavioral processes that might contribute to obesity.

Although neuroimaging technologies have identified a variety of brain areas in obese and normal weight individuals that are differentially activated in response to various manipulations, such differences cannot be assumed to reveal the brain processes that underlie vulnerability to chronic positive energy balance and weight gain. That is, because the development of obesity could both produce and result from characteristic patterns of resting and stimulated brain activity, the documentation of such differences cannot provide definitive information about brain-based predispositions that may underlie the development of obesity. Furthermore, past research has clearly shown that there is tremendous variation within normal weight and obese groups on variables that may be relevant to the development of obesity (e.g.[1,4]). Such variables include negative affect [5], responsiveness to internal and external cues [1,6], food craving [7], restrained eating and disinhibition [8] and binge eating [9]. It is important to understand the neural underpinnings of variables such as these in both normal weight and overweight populations, albeit for somewhat different reasons.

For some normal weight individuals, particular differences in appetite-related dimensions could identify predispositions that contribute to a chronic positive energy balance, weight gain, and eventual overweight or obesity. On a population basis, preventing obesity is likely to play a major role in curbing and reversing the obesity epidemic. Therefore, identifying those who are predisposed to gaining weight could provide valuable insights into the most effective approaches toward obesity prevention. For overweight and obese individuals, the existence of significant heterogeneity in relevant variables suggests that there likely are several "obesities," rather than a single condition of obesity caused by a uniform set of influences. Given this, determining the major influences underlying particular types of obesity could be key to developing more effective prevention and treatment approaches.

Finally, the processes that contribute to weight gain and obesity (e.g., overconsumption of foods high in sugar or fat [10]), the physiological effects of excessive adiposity itself, [11] or both, could produce long-lasting neurophysiological changes[12]. Tataranni and Ravussin [13] have reviewed evidence that certain peripheral physiological states that predispose people toward accelerated weight gain (e.g., low insulin sensitivity and low plasma leptin concentrations) gradually normalize as weight is gained and sometimes actually reverse direction as obesity is developed and maintained (e.g., the insulin resistance and high leptin levels often seen in obese individuals). It is not known if similar adaptations occur at the neurophysiological level, but two observations suggest that they might. First, an EEG study of normal weight restrained eaters (who are susceptible to disinhibitory eating) found that they had greater tonic right-sided prefrontal activity than unrestrained eaters [14]. In obese individuals, higher scores on the Three Factor Eating Questionnaire (TFEQ) Disinhibition Scale were found to be related to greater *left*-sided prefrontal activity [15]. Thus the relationship between prefrontal asymmetry and measures of disinhibitory eating was reversed in normal weight and obese individuals. A second possible example involves sensitivity to reward as determined in part by the brain's dopamine system. There is evidence that obese individuals score higher on reward sensitivity and have a more pronounced dopaminergic response to food stimuli, but that they have fewer dopamine D_2 receptors, possibly as a result of reward-related over-stimulation of the dopamine system [16,17]. Though speculative at this point, it is possible that heightened dopamine release in reward centers is a risk factor for excessive food intake among normal weight individuals and that those who become overweight show a resulting down-regulation of dopamine receptors that produces a heightened need for food reward to reach an acceptable level of hedonic satisfaction. This process could produce the oft-observed satiety deficits in obese individuals [18].

Because the effects of variables associated with weight gain may change as a consequence of weight gain, it is difficult to disentangle correlation and causation. Therefore, rather than reviewing neuroimaging studies that found clear differences in activation between normal weight and overweight or obese populations, we reviewed studies that focused on the neural correlates of individual differences measures within normal weight and overweight populations in order to gain a better understanding of how those individual differences might be relevant to the prediction of weight gain (in normal weight individuals) or to the development of treatments (for overweight individuals). (When we refer to the activation of brain regions below, we are referring to increased blood flow associated with increased metabolic demands of neurophysiologically-activated neurons.)

We now turn to a review of topics involving neural correlates of individual difference measures of appetite. We begin with general models of food intake motivation.

2. Motivations for food intake

Food intake is regulated by a complex interplay of physiological, environmental, and cognitive factors. In a state of caloric deprivation, physiological hunger signals generally take primacy over cognitive factors, such as a drive for thinness [19]. However, evidence suggests that most eating in food-abundant environments occurs prior to the development of significant energy depletion and, in fact, occurs to prevent physiological hunger [20]. The drive to eat that results from, or prevents, true energy deprivation can be referred to as homeostatic hunger [6]. Lowe and Butryn [6] recently described a related but distinct motivation for food intake, driven by the reward value of palatable foods in the absence of energy need. Evidence suggests that the reward value of food may either override internal signals of satiety [21,22] or lead to the development of a separate motivation to consume palatable foods purely for their hedonic appeal (so-called hedonic hunger; see [6]).

With the wide availability of inexpensive, highly palatable and calorically dense foods, most individuals in developed countries can easily obtain enough food to maintain caloric homeostasis. Thus, homeostatic eating motives may only rarely develop and the taste of food may be replacing normal hunger as the determinant of an increasing proportion of energy intake. Individuals are frequently forced to balance an immediate drive for hedonic reward with more distal desires to maintain health and a healthy body weight. Unfortunately the most pleasurable foods are often also the most calorically dense [23,24]. Foods frequently involved in binge episodes (pizza, hamburgers, cookies, chips, desserts, etc.) are usually associated with the highest anticipated reward [25–27] and are more likely to activate reward-related brain areas [28–30], described below. It has been suggested that the motivation to ingest foods high in energy density developed in humans through evolution [31,32]. Neural sensitivity to oral rewards is shown to be present in infants [33], and exists independently of familiarity or learning [34]. This desire for energy dense foods, even in the absence of physiological hunger, would have conferred a strong survival advantage by driving individuals to consume as much energy as possible when surplus food was available. Because the majority of surplus energy is stored as fat, this would help ensure survival during intermittent periods of food scarcity [31,32,35].

2.1. Food reward in the human brain

There are several areas in the brain thought to be involved in reward processing, particularly the mesolimbic (dopaminergic/opiod) system, which extends from the ventral tegmental area of the midbrain to the nucleus accumbens (NA) in the striatum and

includes the prefrontal cortex (PFC), amygdala, and hippocampus. A number of imaging studies report increased brain activation in areas associated with the reward value of food in the mesolimbic system when exposed to highly palatable versus less palatable food stimuli [36–40]. This may help explain physiologically hungry humans' increased sensitivity to sweet tastes, and their greater likelihood of liking novel tastes [41,42]. Additionally, activation of the mesolimbic/dopaminergic reward system in response to palatable foods in the absence of hunger may reflect the hedonic appeal of these foods. Evidence suggests that activation of this system is powerful enough to promote food consumption beyond physiological satiation [21,22,43–45]. In addition, direct pharmacological activation of this network in animals that are already fed beyond satiety produces hyperphagia and increases preferentially the intake of foods high in fat and sugar [37,46].

Dysregulation of the mesolimbic reward system may contribute to the development and maintenance of obesity [47]. Although the attenuation of dopaminergic signaling can lead to compensatory overeating [48], evidence suggests that over-activation of the mesolimbic system also promotes heightened reward sensitivity and overconsumption [37,49–51]. Individual differences in measures of trait reward sensitivity (a heightened responsiveness to biologically-motivated reinforcement value, thought to be mediated by the mesolimbic system and influential in controlling appetitive behavior) predict food cravings, hyperphagia, and relative body weight [52–54]. In addition, Beaver et al. [55] demonstrated that individual differences in trait reward drive in normal weight individuals, assessed using the Behavioral Activation Scale [56], were strongly correlated with neural activation in response to pictures of appetizing foods in areas implicated in reward, including the ventral striatum, amygdala, substantia niagra, orbitofontal cortex, and ventral pallidum. It is also possible that a relative inability to inhibit caloric overconsumption may additionally contribute to obesity [32,51]. It should be noted, however, that it is not yet clear which specific effects help cause, or are caused by, an obese state.

2.2. Brain-based models of appetitive motivation

Three theoretical frameworks have been proposed that attempt to relate particular neural circuits to the evaluation of (typically omnipresent) appetitive stimuli and the initiation of behavioral responses (i.e., food intake). It has been posited that initial human evaluation of external stimuli in the brain can be reduced to two primary reactions on an affective dimension (positive versus negative [57,58]), a motivationally-based dimension (a tendency toward approach versus withdrawal [59,60]), and a third behaviorally-based dimension (behavioral activation versus inhibition [56,61,62]). These three approaches are not equivalent but are all thought to be regulated by the same network within the mesolimbic system and may help elucidate the strength of drive toward, and the ability to resist, consumption of high palatability foods.

According to Davidson's approach- and withdrawal-related affect model (affect model [63]), human emotion is a functional byproduct of the stimulus evaluation process in the human brain. That is, in evaluating emotionally relevant stimuli (evolutionarily necessary for survival), we experience positive or negative affect as a result of the brain's assessment of that stimulus, which quickly and non-consciously categorizes it as appetitive (desired) or aversive (to be avoided) and initiates action towards (approach) or away from (withdrawal) it [58,64]. Two basic circuits have been proposed, each mediating different forms of emotion [65–67]. The approach-related positive affect system facilitates appetitive behavior and generates positive affect (e.g., enthusiasm, pride, agency [68]). It should be noted that the activation of this system is hypothesized to be specifically associated with pre-goal attainment positive affect, elicited as a person moves closer toward a specific appetitive goal

[69,70]. Evidence also suggests that there is a second system concerned with the neural implementation of withdrawal [57,58]. This system facilitates the withdrawal of an individual from sources of aversive stimulation and generates certain forms of negative affect that are related to withdrawal [58]. For example, both fear and disgust are associated with increasing the distance between the organism and the source of aversive stimulation [64,66].

Substantial individual differences exist in the tonic level of activation of the affective valence system, which are related to an individual's propensity to experience either positive or negative affect, both dispositionally and in response to emotionally relevant stimuli [58,64]. Research suggests that affect in the human brain is controlled primarily by the PFC [57,83]. Within the PFC, there exist at least three separable neural systems, the orbitofrontal, ventromedial, and dorsolateral cortices, all of which are involved in affect regulation, complex goal-directed behavior, and feeding [36,51]. Recent evidence suggests that these systems within the PFC may regulate both excitatory and inhibitory reactions to appetitive stimuli, [32,51,55]. The propensity to experience more positive or negative affect has been shown to be related to asymmetrical activation (more activation in one hemisphere as compared to the opposing hemisphere) within the PFC, referred to as "prefrontal asymmetry" (see [58] for a review). Several neuroimaging studies have related positive affect to left-sided prefrontal asymmetry (i.e., the ratio of left- to right-sided prefrontal activation at rest is greater than 1 [57,64,71]) and have related negative affect to right-sided prefrontal asymmetry [57,58,72]. Thus, according to Davidson's affective theory, individuals showing right-sided prefrontal asymmetry are more likely to experience negative affect and avoid experiences that might generate emotional distress (as reflected, for example, in elevated scores on measures of depression and anxiety). Conversely, individuals with more left-sided prefrontal asymmetry are theorized to be more likely to experience positive affect and to seek out experiences that might generate reward (despite the risks this often entails).

Harmon-Jones and Allen [73] proposed that motivational direction (approach–withdrawal), as opposed to affective valence (positive–negative) may be the critical factor in stimulus evaluation and the initiation of motivated behavior. Evidence supporting the contention that affective valence and motivational direction are dissociable came primarily from studies demonstrating that when individuals experienced anger (a negative emotion), they also showed a tendency to approach the (anger-causing) stimulus and displayed a pattern of prefrontal activation consistent with approach behavior (i.e., a predominance of left- over right-sided activation [73]). According to this motivational direction hypothesis, when evaluating external stimuli, individuals will experience a drive to approach or withdraw from stimuli, irrespective of associated affect. Therefore, although most appetitive stimuli will be associated with positive affect and approach, and most aversive stimuli will be associated with negative affect and withdrawal, exceptions to this rule can occur. Harmon-Jones work suggests that when this happens, approach or avoidance behaviors are more influential in determining prefrontal activation than the affective state that is simultaneously experienced [59,60].

Finally, Gray [74] and Gray and McNaughton [61] proposed an additional framework for the evaluation of stimuli and initiation of motivated behavior involving three core systems; the behavioral activation system (BAS), fight–flight freezing system (FFFS), and the behavioral inhibition system (BIS). Although originating from personality theory, independent of brain activation, dopaminergic neurotransmission has been proposed as playing a central role in this framework because of the implication of mesolimbic and mesocortical pathways in reward-directed behavior [75]. The BAS serves to activate goal-directed behavior. It mediates on-going goal-directed behavior and is engaged by stimuli signaling reward or safety (omission of punishment). The FFFS also serves to activate goal-directed behavior and mediates avoidance behavior. The FFFS is activated by stimuli

signaling punishment or frustrating non-reward. The third system, the BIS, is engaged whenever there is a conflict between competing alternatives — that is, when it is unclear which behavior will result in the best, or least bad, outcome. The BIS serves to inhibit on-going behavior in an attempt to further assess behavioral options before acting. The BIS does this by increasing arousal and vigilance in order to allow the individual to choose the optimal behavior. This conflict can arise when there are competing good alternatives (approach–approach conflict), a reason for approaching a threatening stimulus (approach–avoid conflict), or competing bad or threatening alternatives (avoid–avoid conflict).

Because in modern times it is assumed that the FFFS system is rarely engaged, it has been removed from Gray's model. Thus, any conflict between competing alternatives in deciding how to act in order to achieve a particular goal (either gain reward or escape punishment) is proposed to engage the BIS, resulting in an inhibition of on-going action and a more careful consideration of competing options. Conversely, stimuli presenting clear opportunity for reward or safety, without conflict, are proposed to engage the BAS. BAS activation results in non-conflicted/on-going or motivated action, either towards an appetitive goal, or towards safety (away from aversive stimuli). In terms of anatomical instantiation within the brain, the BAS system has been most well-studied, with research showing associations between measures [56] of behavioral activation and both activation and grey matter volume in mesolimbic areas including the ventral striatum, orbitofrontal cortex, and the amygdale [55,76]. As with both prior theories, the BIS–BAS theory is also posited to be associated with prefrontal asymmetry. Evidence has demonstrated that behavioral activation is associated with left-sided prefrontal asymmetry [62,77,78], while behavioral inhibition has been shown to relate to right-sided prefrontal asymmetry [62,77,78]. Similarly, large individual differences are proposed to exist in the tendency to become behaviorally activated (or inhibited) in response to external stimuli. For example, an individual high in BIS tendencies might be someone who can never make up their mind and struggles with every decision; the BIS–BAS model would predict that this individual would show right-sided frontal asymmetry. Conversely, an individual high in BAS tendencies would be quite decisive and quick to seize opportunities — that is, their behavior is more influenced by the allure of obtaining rewards than by the fear of incurring punishment. Such an individual would be predicted to show left-sided frontal asymmetry.

Thus, the affect model focuses on the affective valence (positive versus negative) associated with emotionally relevant stimuli. The motivational direction model focuses on whether external stimuli evoke an approach or withdrawal response to best meet the needs of that individual, irrespective of affective valence. The BIS–BAS model focuses on the absence or presence of goal conflict, irrespective of affective valence or motivational direction. All three theories propose that the tendency to act in a particular manner is reflected via prefrontal asymmetry. In addition to their respective representations through prefrontal asymmetry, these theories all assume that these tendencies are trait-like in nature and that large differences exist between individuals in the directionality of such propensities.

The above theories represent three of the most widely applied explanations of human stimulus evaluation and action initiation processes. Recent evidence suggests that this cognitive evaluation process may exert heavy control over human feeding [14,21,22,43–45]. As noted by Alonso-Alonso and Pascual-Leone [79], human ingestive behavior is different from that of most other living species in that it is not chiefly driven by the need for subsistence, but has evolved into a more complex behavior that carries social and cultural messages [80,81]. Individuals judge what is appropriate to eat according to affect, past experiences, cultural norms, and particularly future predictions (i.e., expected reward value). These authors [71] point out: "This essentially human, cognitive dimension of eating may play a critical and insufficiently emphasized role in obesity" (p. 1819). Petrovich and Gallagher [45] further demonstrated these influences in rats by creating environmental cues that acquire motivational

properties through Pavlovian conditioning [82]. These authors found that such cues subsequently trumped biological satiety signals and promoted eating in sated rats [45]. Tataranni and Del Parigi [83] suggest that "As eating is often driven by the hedonic value of food, the brain response to the affective component of taste and olfaction may contribute to what and how much we eat" (p. 233).

2.3. The prefrontal cortex: evaluation of food stimuli

Although several areas are involved, the PFC is proposed as the primary area responsible for the evaluation of stimuli and initiation of responsive action in the human brain [32,57,67,84,85]. The PFC is asserted to contain and maintain desired end states and, based on past experience, evaluate competing alternatives and ultimately direct action potentials in a manner that will either move the organism closer to reaching a desired end state (achieving reward or escaping punishment). The PFC becomes most important when "top-down" processing is required; when behavior must be guided by internal states or intentions, particularly when there are competing alternatives. A common example of this is in the case of delayed gratification, where an immediately available reward may impede the acquisition of a more long-term goal (e.g., choosing not to eat a desired desert in the hopes of maintaining body weight). In this case, the PFC would be required to produce a bias signal to other brain regions that guide behavior to the more desired goal. The effect of these bias signals is to guide the flow of neural activity along pathways that establish the proper connections between inputs, internal states, and outputs needed to obtain a desired end state. Miller and Cohen [85] describe this flow of neural activity for goal-directed decision making "activity flow" and relate the function of the PFC to that of a switch operator in a system of railroad tracks. Within this model, the brain is seen as sets of tracks (pathways) connecting various origins (e.g., stimuli) to destinations (responses).

Several researchers have noted an association between appetitive behavior and activation in the prefrontal cortex (PFC [14,79,86,87]) and others have suggested a prominent role of PFC activation in the central regulation of eating [3,79,83,87,88]. Several authors have found increased activation in the PFC with exposure to food cues, ([30,89,90] gastric stimulation [91] and following food intake [83,88,92,93]. In addition, larger increases in PFC activation have been found in obese versus lean individuals [88,93], potentially reflecting a heightened sensitivity to hedonic reward [55,90,94,95].

2.4. Lateralization of activity in the prefrontal cortex

There is a growing body of literature suggesting that overall PFC activation may be less relevant to feeding than the hemispheric lateralization of activation in the PFC. Several strands of evidence implicate the right hemisphere of the PFC as being most directly related to the cognitive control of food intake [30,85,87,96–100]. In fact, Alonso-Alonso and Pascual-Leone [79] recently suggested that a dysfunction of the right PFC may represent a central event in the etiology of human obesity; "Beyond dysregulation of appetite and overactivity of food-related reward and motivation loops, it is possible that disruption of the right PFC is a critical mechanism sufficient to cause a positive switch in energy balance, favoring an increase in body weight in modern societies" (p. 1821). However, there is evidence that left hemisphere PFC activation is also involved in the regulation of food intake [83,92,93,101].

Beaver et al. [55] found increases in left PFC during exposure to appetizing foods, but also reported increases in activation in the right PFC during exposure to "disgusting" foods. The aforementioned theories of stimuli evaluation would posit that exposure to appetizing foods increased positive affect (affective), approach motivation (motivational direction), and/or behavioral activation (BIS–BAS). Conversely, exposure to disgusting foods would be posited to have increased negative affect, withdrawal motivation, and/or behavioral inhibition. Similar applications of these

theories can be superimposed on the growing body of literature describing prefrontal asymmetry in relation to food cues and food intake. For example, Andreason et al. [102] (using PET) scanned participants during a standard non-food-related task and found that bulimic women displayed greater left-sided activity in the PFC. Karhunen et al. [103] (using SPECT) found that, as compared to non-binge eaters, obese binge eaters displayed a greater increase in left-sided prefrontal asymmetry following exposure to palatable food. In addition, strong linear correlations were observed in this group between left-sided PFC activation and an increase in hunger during the exposure to food, suggesting a relationship between asymmetrical activation of the PFC and binge eating behavior [103]. In 2002, Silva et al. [14] (using EEG) found that normal weight restrained eaters exhibited greater tonic right-sided prefrontal asymmetry as compared to normal weight unrestrained eaters. In addition, state affect was not found to mediate this relationship, suggesting an independent relationship between a measure of appetitive behavior and prefrontal asymmetry in humans. Ochner [104] found that left-sided prefrontal asymmetry was correlated with measures of disinhibition, hunger, and appetitive responsivity in overweight individuals.

Although the debate about which theory is most comprehensive in describing the stimulus evaluation and response initiation process in the human brain has already waged for more than a decade, it has only recently begun within the specific area of food stimuli and eating behavior. It should be noted that the affective, motivational direction, and BIS–BAS theories are oriented toward general features of behavior and undoubtedly represent only a fraction of the influences and brain areas that ultimately control feeding. These perspectives may inform a model of eating regulation but far more research is necessary in order to propose a comprehensive model of how various brain areas interact to determine eating in particular circumstances and over time.

3. Measures of impulsivity, craving and binge eating

Today's obesogenic environment encourages consumption of both large portions and of foods high in energy density. However, some individuals may be more prone to problematic overeating (i.e., repeatedly consuming energy beyond energy needs), which over time leads to weight gain, difficulty losing weight, and potentially psychological distress. Relevant topics related to overconsumption are binge eating, high impulsivity, and food cravings. Thus, individuals reporting binge eating episodes, those high in measures of impulsivity, and those reporting frequent food cravings that are difficult to control may represent particularly at-risk populations. Questions remain about why some individuals have more trouble controlling food intake than others, regardless of weight status. The following represents a review of the three concepts and relevant findings from neuroimaging studies. Of note, although we treat impulsivity, binge eating, and food cravings as three distinct categories, we recognize that they are related and can co-occur. Indeed, impulsivity is often associated with binge eating, as are food cravings. However, not all individuals high in impulsivity engage in binge eating. Additionally, while food cravings are often associated with severity of binge eating, food cravings are much more common than is binge eating and cravings are not necessarily associated with increased eating [105]. Thus, even though there is significant overlap between the three topics, we feel it is important to address them as distinct categories to understand how each may contribute to weight and eating behavior.

3.1. Impulsivity

Impulsivity is conceptualized as a stable trait. Beyond that, various operational definitions of impulsivity have been proposed. It is now generally agreed that the term impulsivity encompasses a wide range of traits, rather than a one-dimensional construct. Various subtypes of impulsivity have been proposed that are only moderately inter-correlated. Researchers have suggested that impulsivity consists of

three broad dimensions, based on the most widely used self-report measures of impulsivity [106]. The first can be termed "urgency," which is the tendency to respond immediately, and without thinking about consequences, to internal (positive/negative affect) and external stimuli [107]. The second is the inability to delay gratification or tolerate boredom [107]. The third can be termed "sensation seeking." This refers to the tendency to seek out novel or exciting stimuli. Behavior labeled "impulsive" may result from increased drive for pleasure or reward, by decreased inhibitory ability, or both.

The most commonly used measures of impulsivity include the Dickman Impulsivity Inventory (DII), the Eysenck Impulsiveness Questionnaire (I$_7$), the Barratt Impulsiveness Scale (BIS-11), and Carver and White's appetitive behavioral approach system (BAS) and avoid behavioral inhibition system (BIS) scales [56]. A behavioral measure is also often used (e.g., the go/no go task, which measures ability to inhibit motor responses). The DII distinguishes between functional impulsivity and dysfunctional impulsivity (rash decision making). The I$_7$ assesses impulsiveness and venturesomeness (being conscious of a risk but acting anyway). Lastly, the BIS-11 (derived from the BIS/BAS) assesses frequency of impulsiveness-related behavior or cognitions [106].

The trait of impulsiveness may be another important individual difference variable in identifying those most vulnerable to overeating and weight gain [108,109]. Binge eating has frequently been associated with impulsivity, particularly with urgency (the tendency to respond immediately and without thinking about consequences) in response to affect [107,110]. In general, more impulsive individuals may have more difficulty stopping themselves from eating palatable foods or eating in response to emotion, which could then contribute to weight gain or to making weight loss more difficult. A relationship between obesity and impulsivity has also been frequently described [111]. Obese individuals show a preference for smaller, immediate rewards, rather than larger delayed rewards, indicating poor and impulsive decision making [52]. Impulsivity is also associated with higher weight in children [111,112].

Several brain areas have been shown to be associated with different types of impulsivity. The prefrontal cortex, including the OFC, is critical for decision making and response selection [113]. Distinct regions of the PFC work together with the striatum, forming a network responsible for processing reward information, reward-related learning, goal-directed acquisition, and formation of habits. Cognitive control of behavior is thought to depend on the OFC. Other research suggests that the role of the OFC might not be to inhibit impulsive behavior but to assess and update the value of an outcome under changing conditions (e.g., the inability to alter behavior despite a decrease in the value of the outcome) [114]. A functional brain imaging study in humans reported that effectively inhibiting performance during the go/no go task positively correlates with activity in the right ventral frontal lobe, dorsolateral prefrontal lobe, and anterior cingulate gyrus [115,116].

Although there is growing evidence that different measures of impulsivity correlate with food intake and body weight [109,111,117], little research has been done on neural correlates of impulsivity as it relates to appetite. Most notably, Beaver et al. sought to illustrate the role of a network of interconnected brain regions, comprising frontal, ventral striatal, amygdala, and midbrain regions in response to food reward [55]. To do so, they examined the relationship between the BAS-drive scale, which is thought to closely reflect individual differences in the activity of ventral–striatal-related circuitry [75], and neural responses to appetizing foods (e.g., chocolate cake, pizza) using fMRI in 14 right-handed healthy volunteers. Beaver found that BAS-drive scores significantly predicted activation to appetizing foods (relative to bland foods) in the right ventral striatum, the left amygdala, the substantia nigra/ventral tegmental areas of the midbrain, the left OFC, and anterior and left ventral palladium (all areas of reward). They suggested that this finding illustrates how variation in the BAS-drive trait is manifested by the

extent to which this reward network is activated. Exposure to palatable food cues can override satiety signals and promote overeating and this perhaps is particularly likely among those who are most highly motivated to obtain food reward. Further support for this view came from a study by Volkow et al., who showed that amplification of the dopamine (DA) signal in participants via a small dose of oral methylphenidate increased their desire to eat in response to a palatable food cue [118], implicating the important role of dopamine and highlighting the similarities between impulsivity as it relates to eating and drug abuse [53].

3.2. Cravings

Food cravings are generally defined as an intense desire to eat a specific food [119,120] and difficulty resisting that desire [121]. The intensity of the craving distinguishes it from an ordinary desire to eat, while the specificity of it distinguishes it from regular hunger. Food cravings are measured by self-reported desire to eat a specific food. Food cravings are extremely common, with a survey showing 100% of young adult females and 70% of young males reported at least one food craving event in the past year [122]. Heightened sensitivity to food cravings and not being able to control cravings may also underlie overeating and weight gain. This is particularly important to examine in an environment where food is readily available and craving triggers are everywhere. Indeed research has found associations between food cravings and BMI [121] and binge eating [123]. Very few studies have explored individual differences in neural correlates of food cravings. Studies have typically looked at food pleasantness and likeability of foods, rather than craving for the foods specifically. Those studies have found food desirability to be associated with OFC activity [26,94,124]. One study that specifically compared individual differences in food craving was by Pelchat et al. [119]. They used fMRI in healthy participants to study the impact of a monotonous diet (1.5 days of vanilla-flavored Boost) on food cravings and related brain activation. On the day of the scan, participants were asked to identify foods that they "really liked" and were then shown those foods names and asked to think about that food's taste, smell, and texture while the word was on the screen, as well as their level of food craving when viewing that food's name. In the monotonous diet group, compared to the healthy control group, there was greater activation in the hippocampus, insula, and caudate when asked to visualize the craving-inducing foods. These areas are also activated during drug cravings. The authors suggested a common pathway for desire in both natural and pathological rewards.

Another study specifically examined food cravings by using fMRI to compare brain responses to chocolate in chocolate cravers versus non-cravers [125]. Participants were 16 healthy females, divided equally into cravers and non-cravers with the Chocolate Cravers questionnaire (CCQ-T [126]). While in the scanner, participants were shown a picture of chocolate, received a small amount of liquid chocolate into the mouth, and viewed a picture along with the oral stimulus. The medial OFC was found to be more activated in cravers than in non-cravers by the sight of chocolate and chocolate in the mouth. Additionally, there was greater activation in the anterior cingulate cortex (ACC) in cravers versus non-cravers to the combination of viewing and tasting chocolate. The ventral striatum showed greater activation in cravers versus non-cravers to the chocolate image alone. This area was activated in all participants, with no significant differences between groups, in response to chocolate in the mouth. The OFC connects to both the ACC and the ventral striatum. The authors suggested that these brain regions react strongly to the rewarding elements of a craved food and also are involved in the effects of visual stimuli on food cravings, underlying the importance of conditioned cues. In this study, the authors suggest a neural network in which chocolate cravers are more responsive to the conditioned incentive value of the craved food, thus making it more difficult to control the craving.

3.3. Binge eating

Clinically significant binge eating can be defined as clearly eating more than the average person in a short period of time while experiencing feelings of loss of control, occurring at least twice a week for 6 months. Other common aspects of binge eating include eating alone, eating rapidly, feeling physically uncomfortable after eating, and feeling guilty after eating. Binge eating is associated with obesity, particularly severe obesity (BMI>40 kg/m^2), and eating disorders (bulimia nervosa; BN). Individuals are often divided into binge eaters or non-binge eaters; however, bingeing should be viewed as continuously, rather than discretely, distributed. Binge eating disorder (BED) is currently classified under Eating Disorder Not Otherwise Specified (EDNOS) in the DSM-IV-TR (APA [127]). Also included in this category is probable BN (PBN), which is defined in terms of binge eating episodes and compensatory behaviors that occur less than twice a week or for a duration of less than 3 months (APA [127]). PBN was found to be more common in a large sample of college students than BN that meets full criteria [128]. Sub-threshold BED, which is recurrent binge eating but at a less frequent rate than full-blown BED, is also found to be more common in the general population than BED. Additionally, many ED and non-ED individuals experience subjective binge episodes (i.e., feeling out of control while eating what is considered an appropriate amount of food) that may not contribute to weight gain but are experienced as emotionally distressing. Some common ways to measure binge eating include structured interviews (e.g., the Structured Clinical Interview for the DSM-IV, the Eating Disorder Examination) and self-report measures (e.g., the Binge Eating Scale; the Eating Disorder Inventory; Questionnaire on Eating and Weight Patterns). Recurrent binge eating has been shown to be associated with elevated body weight [129] and has been found to be significantly correlated with various indicators of emotional distress and psychopathology [130]. For example the disorder of BN-EDNOS is more common than BN that meets full DSM-IV-TR criteria.

Neuroimaging research has begun to explore the neural correlates of binge eating to help answer the question of why some individuals engage in binge eating, regardless of weight status. Schienle et al. [131] used fMRI to study whether binge eaters would be characterized by an elevated reward sensitivity (as measured by the BIS/BAS scales) and increased activation in reward processing brain areas while viewing pictures of high-calorie foods (e.g., French fries, ice cream) compared to disgusting items (e.g., maggots) and neutral items (e.g., household objects). They studied 17 females with BED, 14 with BN, 19 normal weight controls, and 17 overweight controls, all scanned following an overnight, 12-hour fast. Food images rated as pleasant and appetizing were accompanied by activation for all groups in the anterior cingulate cortex (ACC), the orbitofrontal cortex (OFC), and the insula, suggesting a basic appetitive pattern. BED patients scored highest on the BAS scales compared to both BN patients and normal weight and overweight controls and had greater activation in the medial and lateral OFC compared to BN patients. Relative to the controls, BED patients had greater medial OFC involvement. The higher BAS scores and greater OFC activation supports increased reinforcement sensitivity in BED patients. The findings are also consistent with those of Beaver et al., [55] described above, which found a correlation between the BAS scores of healthy participants and OFC activity. Heightened medial OFC reactivity to food cues might translate reward drive into compulsive overeating in BED patients. As with BED patients, medial OFC activity was also positively correlated with BAS scales in BN patients, adding further support for the suggested role of the OFC in mediation of reinforcement sensitivity. Geliebter et al. [40] compared obese (BMI>29) binge eaters (n=5); obese non-binge eaters (n=5), lean (BMI 20–24) binge eaters (n=5), and lean non-binge eaters, using fMRI. To be classified as a binge eater, participants had to report regular subjective overeating with loss of control, without needing to meet full BED criteria (sub-threshold BED). Participants were scanned 3 h after consuming a 650-calorie meal and

viewed stimuli representative of binge type foods (desserts and high-fat snacks), non-binge type foods (fruits and vegetables), and neutral food stimuli. Obese bingers had the greatest activation as a whole and were the only group to show activation in the right frontal precentral region in response to binge food stimuli, an area involved in planning motor behavior. The authors suggested that this may reflect motor planning about eating the binge foods. Additionally, obese binge eaters responded to binge type foods with more activation than obese non-bingers and both lean groups in the dorsolateral prefrontal cortex, the OFC and the lingual cortex. As with previous research [103], they found more activation in prefrontal cortex compared to non-binge eaters in response to food stimuli and in particular binge food stimuli. The prefrontal cortex is typically found to be activated more in obese individuals when compared to lean individuals, however, those studies have not separated obese subjects into binge and non-binge eaters. Geliebter and colleagues suggested that greater activation in the prefrontal cortex may be more reflective of a component of binge eating rather than of weight alone.

Karhunen et al. [103] compared 8 obese binge eating women to 11 obese non-binge eating women and 12 normal weight non-bingeing women using single photon emission computed tomography (SPECT). Binge eaters were defined by three self-report measures and a clinical interview. Non-binging women (obese and lean) were recruited from a previous study [132]. Participants were tested in a fasted state only and exposed to a meal that was placed on a table in front of the participant. Feelings of hunger and desire to eat were assessed three times during the food exposure phase: just before being exposed to food, directly following the injection of the tracer and exposure to food, and at the end of the food exposure phase. They found that exposure to food elicited different changes in regional cerebral blood flow (rCBF) in obese binge eating women than in obese or normal weight non-binge eating women. This was seen particularly in the frontal and prefrontal regions of the left hemisphere, showing greater increases in blood flow due to exposure to food. In addition, correlational analyses showed that increases in feelings of hunger during food exposure (from the beginning of the food exposure period to the end) were associated with higher rCBF in the left frontal and prefrontal cortices. The authors suggested that the left hemisphere, and its frontal and prefrontal cortices, is associated with the regulation and reward of eating behavior. Karhunen et al. [103] suggested that the balance of cerebral hemisphere activity may play a role in binge eating behavior in humans, although it may also depend on the individual's eating state (anorexic or binge eating phase). The investigators further postulated that the observed changes in rCBF of the frontal and prefrontal regions in binge eating subjects from food exposure could reflect binge eaters' preoccupation with food and eating. Further support for this theory comes from the fact that bulimic subjects have shown greater left than right hemispheric asymmetry in the frontal cortical regions [102,133].

The above review of neuroimaging research on aspects of overeating (including binge eating, impulsivity, and food craving) provides some illumination on why at times certain individuals might find controlling food intake particularly difficult, if not impossible. The OFC was found to have greater activation in the groups more likely to engage in overeating, suggesting that it plays an important role not only in determining food value but also in connections it makes to other parts of the brain that might control behavior and drive. Examples might be the insula and the ACC, both areas which, taken together with the OFC, might produce "goal-directed" behavior even when the homeostatic need to eat is not present. Additionally, the prefrontal cortex, and particularly the left hemisphere, seems to play a role in overriding satiety signals, thus leading to overconsumption. However, much more research is needed before implications can be made about how this information might impact clinical outcomes. For example, questions remain about whether certain individuals eat more food because of an enhanced reward system or because of less effective generation or processing of inhibitory signals. There is

substantial literature indicating that obese individuals find palatable foods more rewarding [118,134–137], but it is unclear why this is so. For instance, it could reflect a greater intensity of food-based reward or relative insensitivity to rewards signals (e.g., because of down-regulation of dopamine receptors in reward areas) that requires greater food reinforcement before an acceptable threshold of rewarding experience is reached. Less is known about deficits in inhibitory ability; [32,138] however, obese individuals have shown hypo-functioning in the right prefrontal cortex, which is thought to be an inhibitory center [79]. Because the data are from already-obese individuals, we have no way of knowing the extent to which these findings might reflect "primary defects" as opposed to consequences of becoming obese. Studies attempting to resolve this question are needed.

4. Neural correlates of restraint and disinhibition

According to Herman and Polivy [139], eating behavior among weight-concerned individuals emerges from a balance of physiological drives to consume and cognitive efforts to resist the temptation of food. They identified restrained eaters as those who apply cognitive effort to resist the temptation of food, and differentiated them from unrestrained eaters, who respond normally to food deprivation and satiety signals and do not need to apply cognitive effort to control eating and weight. The cognitive effort to resist the temptation of food was called *restraint* [140] by Herman and Polivy, and they measured it with the 10-item Restraint Scale (RS). Tellingly, later research found that restrained eaters (as identified by the Restraint Scale)–and chronic dieters [141]–actually tend to gain weight over time [142,143]. It has been proposed that this counter-intuitive finding may be explained in part by restrained eaters' tendency to cycle on and off diets [144]. Current prevalence of dieting to lose weight among restrained eaters has been reported at 37% [145] and 25% [146], therefore restrained eaters spend most of their time not dieting. What they do while not dieting may be the key to their eventual weight gain.

Herman and Polivy suggest that, restrained eaters, because of their chronic dieting, become vulnerable to various disinhibiting influences [147], such as eating a forbidden food [148], or experiencing negative affect [149,150], drinking alcohol [151], and even experiencing an increased cognitive load [152]. In the well-studied counter-regulation paradigm, restrained eaters become disinhibited after they consume a preload, such as a chocolate milkshake. They subsequently eat more than restrained eaters who have not received a preload, and more than the average unrestrained eater after a preload.

Although restraint as measured by the Restraint Scale was initially conceptualized as a measure of resistance, or inhibition, restraint as measured by the Restraint Scale actually appears to primarily reflect a susceptibility toward disinhibited eating. Partly in response to this problem, researchers developed the Three Factor Eating Questionnaire (TFEQ [8]) and the Dutch Eating Behavior Questionnaire (DEBQ [153]), both of which have measures of disinhibition as well as "pure" cognitive restraint (efforts directed at reduced food consumption). Any review of the neurocorrelates of "restraint" must therefore attend to the fundamental differences between the two types of restraint measures because restraint as measured by the RS appears to measure susceptibility toward disinhibition whereas the TFEQ-R and DEBQ-R scales measure a more homogeneous construct of efforts toward restricting intake. The following review will therefore segregate studies of restraint into two groups, those relying on the Restraint Scale (which reflects susceptibility to disinhibition) and those relying on cognitive restraint, which is a measure of volitional eating inhibition.

Research using the TFEQ and DBEQ scales has shown that high cognitive restraint alone is insufficient to predict counter-regulation; high cognitive restraint must be combined with a tendency to disinhibit. Although counter-regulation has been studied extensively, the neural correlates of the behaviors and states that govern counter-

regulation (and, presumably, the tendency toward disinhibited eating in everyday life) have only begun to be investigated [159].

4.1. Eating inhibition (cognitive restraint)

Kemmotsu and Murphy [154] used electroencephalography to measure olfactory event-related potentials (OERPs) and compare restrained eaters (RE) and unrestrained eaters (URE). Participants were 35 healthy female college students, who were normal weight. Participants fasted for 3 h prior to the recordings. In a within-subjects design, they were all asked to smell six common items, including chocolate and a floral odor. Participants both attended to the odors by estimating their intensities and ignored the odors while completing a visuomotor tracking task during exposure. The two groups differed in how they processed food-related olfactory information. REs had less of a sensory response to olfactory stimuli than did UREs, regardless of whether the stimulus was a food-related or not. However, in sniff tests both groups detected food and non-food smells at similar thresholds and rated them as similarly pleasurable. The authors suggested that ERP was able to detect subtle differences in olfactory function that the psychophysical tests could not detect, and that constant suppression of thoughts about food in REs may explain their smaller attentional allocation compared to UREs. REs also were shown to have attended to food in the attend condition as much as they did in the ignore condition; while UREs were able to decrease attention in the ignore condition. The authors concluded that REs have similar olfactory responses to odors, but are unable to suppress attention to food odor.

In another ERP study comparing REs to UREs, Hachl et al. [155] compared 20 restrained female eaters to 20 unrestrained female eaters (measured by the German version of the TFEQ-R) in a word identification task in which food-related and food-unrelated words were repeatedly presented tachistoscopically. There were no group differences in age or BMI. In each group, half of the participants were tested after a 12-hour fast and half after having broken their 12-hour fast with a 600-calorie muffin preload. Participants were shown words and asked to press a button and read the words. There were three types of stimuli: neutral, food and erotic. Hachl and colleagues found a generally different mode of information processing between the two groups. They speculated that the experiment may have had a greater impact on REs than UREs because it was an explicit task of word recognition that was dependent on hunger state, and therefore REs were putting forth a relatively increased cognitive effort during stimulus identification. The researchers also found an interaction of restraint and preload on stimulus processing that did not depend on stimulus type.

DelParigi et al. [156] used Positron Emission Tomography to test their hypothesis that successful dieters would show increased prefrontal cortical response to meal consumption compared to non-dieters. Their hypothesis was based on the prefrontal cortex's role in intentional control of behavior and the tendency of successful dieters to be higher in restraint (in this case as measured by the TFEQ-R and indicative of inhibition of consumption). The successful dieters averaged a score of 15 on TFEQ-Restraint while non-dieters averaged a score of 9. After an overnight fast, all participants were given a standard breakfast and later presented with 16 randomly ordered solutions of milk/cream and sugar. The participants then produced a rating of subjective hedonic response. They fasted for 36 h between the tasting the solutions and the imaging session. All participants had regional cerebral blood flow (rCBF) measured after the 36-hour fast, again after receiving 2 ml of a liquid meal, and again after a full liquid meal. In comparing relative activation between groups, DelParigi and colleagues accounted for activation in all comparison groups. They found no difference between the successful dieters and non-dieters in subjective hedonic response determined by tasting the solutions of milk/cream and sugar. They also found that after tasting the liquid meal following a fast, successful dieters has similar relative activation in the occipital cortex, hippocampus and parahippocampal gyrus,

compared to a baseline measurement immediately after the fast. Nondieters had greater relative activation in those areas after the liquid meal than they did after the fast. In comparing rCBF after a full meal with rCBF immediately after the fast, they found that successful dieters had greater relative activation in the dorsal prefrontal cortex (DPFC), dorsal striatum and anterior lobe of the cerebellum (ALS) compared to non-dieters. In the same comparison, non-dieters had bilateral orbitofrontal cortical (OFC) activation, whereas successful dieters showed a trend towards deactivation. Overall, participants showed changes in the DPFC that were inversely proportional to changes in the OFC. TFEQ restraint was positively associated with changes in neural activity in the DPFC and negatively associated with changes in neural activity in the OFC when eating to satiation. TFEQ restraint was the only variable associated with changes in activity in the DPFC and the ALS. The DPFC is considered the pivotal site of "top-down" cognitive control of behavior, while the OFC is "a multimodal associative area where sensory and visceral inputs elicited by food ingestion converge and are decoded in their reward value." Because the two areas are thought to be reciprocally interconnected, the authors interpreted their findings to mean that in response to eating a meal, a feedback circuit to inhibit food reward links the DPFC and OFC in successful dieters. They concluded that the correlation between restraint and changes within that circuit may be a mechanism by which TFEQ-REs control food intake.

4.2. Restraint scale and disinhibition

As noted earlier, because behavioral restraint as measured by the Restraint Scale has high concurrent validity with disinhibition measures and is in many ways an opposing construct to cognitive restraint as measured by the TFEQ-R, we are separating the studies based on tendency to disinhibit from the above studies, which were based on inhibition.

Extensive previous research has shown a correlation between affective states and traits, on one hand, and asymmetry of alpha-band activity in the prefrontal cortex (PFC) as measured by EEG, on the other. Specifically, researchers have demonstrated a relationship between right PFC activity and negative affect, as well as a relationship between left PFC activity and positive affect [157,158]. Other research has shown that when restrained eaters with a tendency to disinhibit (RS-REs) experience anxiety, they are prone to overeat [159]. Based on this research, Silva et al. [14] hypothesized that RS-REs would show greater resting right-sided frontal activity compared to RS-UREs at rest. They used EEG to examine prefrontal activity in 23 restrained normal weight female undergraduates and compared their prefrontal activity to 32 unrestrained normal weight female undergraduates. Participants had an 8-minute baseline EEG taken while they sat quietly. Silva and colleagues found that RS-REs had significantly more right-sided prefrontal activity and that normal weight RS-UREs tended to have more left-sided prefrontal activity.

However, in a study seeking to replicate Silva's findings [160], researchers used EEG in the same manner as described above to measure prefrontal activity in 15 restrained eaters and 24 unrestrained eaters and found no significant asymmetry in either group. All participants were normal weight right-handed undergraduate females with no history of eating disorder or significant weight suppression [161]. One difference that may account for the disparate findings was that current dieters were excluded from the study by van Steenburgh and colleagues but not from the study conducted by Silva and colleagues. Evidence has shown that dieting and non-dieting restrained eaters are different in a number of ways [141]. In the later study, participants were also anticipating an ice cream taste test as part of a counter-regulatory study.

In a study using fMRI, Coletta et al. [162] investigated neural activity in restrained and unrestrained eaters (based on Restraint Scale scores). After an 8-hour fast, all participants were scanned while being shown pictures of highly palatable foods, moderately palatable foods and neutral (non-food) images. Participants were subsequently fed a liquid meal prior to

being scanned again and viewing the same picture set. The authors hypothesized that restrained eaters would show greater activation in brain areas associated with hunger and appetitive motivation in response to food stimuli and that the differences between restrained and unrestrained eaters would emerge when compared across states of hunger and fullness.

When fasted and viewing highly palatable foods, UREs showed relatively widespread bilateral activation in areas associated with hunger, expectation of reward and reinforcement [40,83,86,163], compared to restrained eaters. Fasted REs showed increased activation to highly palatable foods only in the cerebellum, an area previously implicated in lower level processing of appetitive stimuli. The authors speculated that the striking difference in activation between the two groups when fasted implies that food-deprived REs do not experience normal deprivation-induced hunger or express hunger differently than UREs. This conclusion is reminiscent of past speculation that obese individuals [164] and normal weight restrained eaters [165] generate weaker hunger signals, do not recognize the hunger signals that they do generate, or both.

When fed and viewing highly palatable foods, REs had activation in the OFC, an area described as being associated with hunger and desire for food [91,163,166], motivation to eat [167], reward expectation [168,169], and food saliency [94]. They also had activation in the left DPFC, left insular cortex, and cerebellum. The finding of cerebellar activity is in accord with a finding by DelParigi et al., [156] discussed above. The authors speculated that the combined activity in several other areas supports the idea that REs are paradoxically more motivated to eat highly palatable food when fed. While fed and viewing high palatability foods, UREs showed relatively more activation in areas related to satiation, inhibition, and memory, a combination that likely allows for regulation of eating.

In addition to studies that have sought to establish the neural correlates of disinhibition in restrained eaters, other researchers have sought to measure the electrophysiology of disinhibition more directly. In an EEG study using a prefrontal asymmetry paradigm similar to that of Silva et al., [14] Ochner et al. [170] examined the relationship between prefrontal asymmetry and cognitive restraint and disinhibition in 28 overweight and obese right-handed adults. They showed a correlation between scores on the TFEQ-Disinhibition and TFEQ-Hunger factors and left-sided asymmetry in the prefrontal cortex. They also discovered that cognitive restraint, as measured by the TFEQ was not associated with prefrontal asymmetry. In the previously described EEG study [160] of normal weight female undergraduates participating in a counter-regulation paradigm, disinhibition as measured by TFEQ-D was correlated with a change in prefrontal asymmetry from left to right after a preload, but was unrelated to prefrontal asymmetry prior to the preload. At no time was prefrontal asymmetry related to food consumption.

Recent neuroimaging research using multiple methods (ERP, PET, EEG, fMRI) has provided some preliminary illumination into how restraint and disinhibition are related not just to eating behavior, but to the objective sensory and cognitive experiences of people when fasted and fed. The research detailed above has also begun to explain and provide some support for theories about the cognitive and motivational processes involved in the anomalous eating behavior of restrained eaters on the Restraint Scale [162], counter-regulation and other eating behaviors. However, much remains to be learned about the neural correlates of restraint, disinhibition, and counter-regulatory eating behavior.

5. Conclusion

EEG, PET, fMRI and other imaging technologies are increasingly being used to localize and describe the functional elements of individual appetitive characteristics, such as prefrontal cortical evaluation of food stimuli, impulsivity, craving, binge eating, and the tendency of food consumption to inhibit or disinhibit subsequent eating. The use of such technologies allows us to begin to break these complex individual differences into their component parts for more discrete analysis. However, due to the multifunctional nature of the disparate neuroanatomical structures involved in such complex behaviors, much future neuroimaging research will be necessary before the neural basis of eating behavior − and its interactions with relevant internal (e.g., hypoglycemia) and external (e.g., food cues) stimuli can begin to be described and subsequent preventive measures or interventions for maladaptive eating behaviors can be developed.

Our review of literature on neural correlates of individual differences in appetite-related measures suggests several directions for future research. First, most studies to date have examined participants' responses to external stimulation such as food or food cues, but studies capable of assessing brain functioning in resting states are also of interest. For example, there are presumably differences in resting brain activity between individuals differing in impulsivity that make those high in impulsivity respond more dramatically when an appealing stimulus is introduced. EEG studies have examined such resting states but other technologies are capable of doing so (e.g., arterial spin labeling or ASL). Second, studies capable of assessing the temporal sequence of brain activation to stimuli could be very helpful in interpreting the results of brain imaging studies. For example, restrained eaters who have recently been fed show activation in limbic and prefrontal areas when shown pictures of palatable foods, but studies capable of determining timing of activation could help determine if this represents "top-down" or "bottom-up" activation [160]. Third, because eating decisions often generate conflict between approach (e.g., anticipated reward) and avoidance (anticipated guilt), it is particularly important to focus on brain areas involved in conflict monitoring and resolution (e.g., the anterior cingulate cortex). Finally, most existing studies have compared obese and normal weight individuals but given the need to prevent weight gain and obesity, more neuroimaging research is needed to understand the appetitive vulnerabilities of normal weight individuals prone to weight gain.

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