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TITLE

Cognitive and Neuromodulation Strategies for Unhealthy Eating and Obesity: Systematic Review and Discussion of Neurocognitive Mechanisms

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Highlights

1) Cognitive training/neuromodulation strategies to reduce unhealthy eating reviewed

2) 6 cognitive, 3 neuromodulation and 1 neurofeedback strategies were identified

3) Response inhibition and goal-oriented trainings reduce BMI and unhealthy eating

4) Stimulation of DLPFC and lateral hypothalamus reduce food craving and intake

5) Studies quality moderately high, but longer duration trials in clinical groups needed

6) Interventions targeting cognitive control are promising for obesity treatment

Abstract

We systematically reviewed research on cognitive training and neuromodulation interventions for reducing food craving/intake, unhealthy diet and weight, and discussed their mechanisms of action. We reviewed 50 studies involving six cognitive trainings: Approach and Attentional Bias Modification, Implementation Intentions, Response Inhibition, Episodic Future Thinking and Working Memory; and four neuromodulation approaches: Transcranial Magnetic Stimulation (TMS), transcranial Direct Current Stimulation (tDCS), Deep Brain Stimulation (DBS) and Neurofeedback. Response Inhibition and Implementation Intentions have shown to reduce unhealthy diet and weight in people with overweight/obesity. Attentional Bias Modification has shown promising results in healthy-weight participants. Brain stimulation of the Dorsolateral Prefrontal Cortex via tDCS and the Hypothalamus via DBS showed benefits for reducing food craving and weight in people with overweight/obesity. Studies quality was generally high, but most trials were short-term and many conducted in healthy-weight samples. Modification of cognitive control and motivational processes/circuits are common mechanisms of beneficial training and neuromodulation interventions, and thus a promising approach for overweight/obesity treatment. Longer duration trials in clinical populations are needed to confirm benefits.

Keywords: Obesity, eating behaviour, unhealthy eating habits, cognitive training, neuromodulation, neurofeedback.

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1. Introduction

The prevalence of obesity has steadily grown worldwide in the last 30 years, and is now considered a global major health concern (Ng et al., 2014). Obesity is associated with metabolic syndrome, cardiovascular disease, type 2 diabetes, asthma, obstructive sleep apnea and many types of cancer, as well as increased risk of dementia (Østergaard et al., 2015; Pandey et al., 2015; Renehan et al., 2008; Wang et al., 2011). People with obesity have medical costs approximately 30% greater than their normal-weight counterparts, posing a challenge for healthcare systems (Withrow and Alter, 2011). Weight loss reduces the health risks associated with overweight and obesity, and is, therefore, encouraged by major international health agencies (NHLBI, 2012; WHO, 2013). The treatment of choice for obesity consists of a comprehensive lifestyle intervention that includes dietary counselling, physical activity and behavior change strategies (Jensen et al., 2013). However, these interventions are costly and very limited in their success, with meta-analytic studies showing that the majority of participants lose no more than 5% of their initial body weight (Magkos et al., 2016). The treatment of choice for severe obesity (Body Mass Index > 35) is bariatric surgery, which aims to restrict the amount of food the stomach can hold through different procedures (e.g., gastric band, sleeve gastrectomy, gastric bypass surgery) (Angrisani et al., 2015). Although the majority of patients achieve a successful degree of weight loss after surgery (> 50% excess weight loss), there is a significant proportion (20-40%) who fail to achieve this goal or who regain weight a few years after the intervention (Adams et al., 2012; DiGiorgi et al., 2010; Karmali et al., 2013; Livhits et al., 2012; Maleckas et al., 2016). In addition, bariatric surgery is highly invasive and linked to other medical complications (Puzziferri et al., 2014). Therefore, there is a clear need for novel approaches to achieve weight loss.

Two novel, promising approaches to weight loss are cognitive training and neuromodulation strategies. These strategies tap into the cognitive and brain mechanisms that underpin unhealthy eating habits. Neuroscience evidence indicates that an overactive bottom-up impulsive system and a weak top-down cognitive control system can bias food choice towards high-calorie foods, which are instantly rewarding (Jansen et al., 2015). The current environment, characterized by the oversupply of highly desirable, energy-dense food, overwhelms cognitive control functions, resulting in unhealthy dietary choices, increased energy intake and weight gain (Berthoud, 2012). Cognitive and neuroimaging studies have reported on the links between obesity and deficits in the cognitive control system (Vainik et al., 2013). In addition, well-controlled animal and human studies have demonstrated that consuming an energy-rich Western diet that is high in sugar and saturated fat can promote not only obesity but also impairments in the brain systems underlying cognitive control (Bruce et al., 2010; Vollbrecht et al., 2016). Thus, it is plausible to suggest that cognitive and neuromodulation strategies focused on strengthening cognitive control will give rise to more effective treatments for overweight and obesity (Smith et al., 2011). Such interventions hold great promise because they actively modify cognitive control skills, rather than relying on the individual's ability to reduce calorie intake and increase physical activity (Turton et al., 2016). This article aims to systematically review the evidence on the efficacy of cognitive training and neuromodulation approaches for reducing food craving and intake, unhealthy diets and weight. Although previous reviews have evaluated cognitive training and neuromodulation studies separately (Jones et al., 2017; Val-Laillet et al., 2015) we sought to provide novel insights by combining both strands of evidence. Given that both cognitive training and neuromodulation capitalize on neuroplasticity, their findings can complementary inform knowledge of therapeutic mechanisms. In addition, we aimed to provide quantitative estimations of the effect size of the therapeutic effects of the interventions, and quality assessments of existing studies. Altogether, these novel aspects will provide the first comprehensive quantitative assessment of the existing evidence, and unique insights about the mechanisms behind the most promising therapeutic approaches.

2. Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses-P 2015 statement for systematic review and meta-analysis protocols (Shamseer et al., 2015).

2.1.Eligibility criteria

Studies were included based on the following criteria: 1) human studies, 2) including adult participants with excess weight (=classified as overweight or obese) or normal weight, 3) applying cognitive training or neuromodulation interventions, 4) using at least one comparison group/condition (except for case series and case reports), 5) including outcome measures of food craving, food choice, food intake, diet and/or weight, 6) published in an international peer-reviewed journal. Studies including participants with primary or comorbid eating disorders (i.e., anorexia and bulimia nervosa, binge eating disorder) and pharmacological interventions were excluded.

2.2. Information sources and search strategy

A literature search was conducted in PubMed, PsycINFO and ScienceDirect in January 2017. The search included all combinations of the following terms: Cognitive Training/Modification or Neuromodulation or specific exemplars (i.e., Approach Bias Modification, Attentional Bias Modification, Implementation Intentions, Response Inhibition, Episodic Future Thinking, Working Memory, Transcranial Magnetic Stimulation or TMS, Transcranial Direct Current Stimulation or tDCS, Deep Brain Stimulation or DBS, Neurofeedback) AND Body Mass Index or BMI, weight, obesity, food consumption, food choice, food valuation or food craving (see details in Supplementary Material). Reference and citation lists were checked for further inclusion of other relevant studies. Abstracts and editorials were excluded. Search results were assessed for inclusion by two independent reviewers (L.F., F.M.). Discrepancies were resolved through consensus or referral to a third reviewer (A.V.).

2.3. Data analysis

The main finding of interest for each selected study was the comparison between the Active intervention and Control on the outcome measures. The mean difference between Active and Control interventions was measured by the Cohen's *d* effect size. For studies utilizing a pre-post assessment, we estimated effect sizes for repeated measures from pre and post means and standard deviations (Morris, 2008). When means and standard deviations were not provided, we estimated the effect size of the Active intervention by transforming *eta squared* (η^2) or *F values* into Cohen's *d* (Lenhard and Lenhard, 2016). Cohen's *d* effect sizes were interpreted as small (≥ 0.20), medium (≥ 0.50), large (≥ 0.80) and very large (≥ 1.30)

(Cohen, 1977; Rosenthal, 1996). A positive Cohen's *d* effect size favors the Active intervention over Control, whereas a negative Cohen's *d* effect size favors Control over the Active intervention.

To assess the quality of the selected studies, two raters (L.F., F.M.) independently evaluated each study using the 13-item quality scale for intervention studies developed by Thompson and colleagues (Thompson et al., 2017). This scale assesses methodological rigor in alignment with the criteria of the Preferred Reporting Items for Systematic Reviews and Meta Analyses-P 2015 recommendations, the Cochrane collaboration criteria and the PEDro guidelines (Bahar-Fuchs et al., 1996; de Morton, 2009; Shamseer et al., 2015). We did not include case reports in this quality assessment (Harat et al., 2016; Whiting et al., 2013).

3. Search results

The search flow and results are displayed in Figure 1. Initial database searches yielded 2199 entries. Thirty additional studies were identified through manual searching of reference lists. After inspection of titles and abstracts, 56 articles were retained for full text review. Six of the 56 articles were excluded since they did not meet inclusion criteria (see details in Figure 1). Altogether, 50 studies were retained for analysis.

The selected studies included six types of cognitive training, namely: Approach Bias Modification (ABM), Attentional Bias Modification (AtBM), Implementation of Intentions (II), Response Inhibition (RI), Episodic Future Thinking (EFT) and Working Memory (WM), and four forms of neuromodulation, namely: Transcranial Magnetic Stimulation (TMS), Transcranial Direct Current Stimulation (tDCS), Deep Brain Stimulation (DBS) and Neurofeedback.

Study designs included up to three different manipulations: (1) Active Training or Neuromodulation, which involves the exercises or brain stimulation parameters that actively target the mechanisms of food intake and weight loss, and are hypothesized to have a beneficial effect on the outcome measures; (2) Active Control, which involves manipulations that are expected to have no effects or negative effects on the outcome measures (e.g., increase unhealthy food choice); and (3) Standard Control, including treatment as usual and no intervention.

The main outcome measures utilized were: (1) Body Mass Index (BMI) and/or body weight measured via automated scales or self-report, (2) food consumption (e.g., sweets consumption, snacking frequency), (3) food choice, (4) food valuation (i.e., subjective ratings of food attractiveness and tastiness), (5) subjective reports of hunger, satiety and desire to eat sensations, (6) food craving, (7) eating styles (e.g., restrained and emotional eating), (8) diet attrition, and (9) performance on cognitive control tasks.

4. Cognitive Training findings, classified by intervention

Table 1 summarizes the design, participants, interventions and main findings of the studies reviewed in this section.

4.1. Approach Bias Modification

4.1.1. Trainings

Approach Bias Modification (ABM) retrains approach bias towards unhealthy food cues by pairing these cues with (1) words related to avoidance (Implicit Association Training) or (2) a motor avoidance response i.e. pushing a joystick (Approach Avoidance Training). ABM has been primarily applied to substance use disorders, and has proven successful at changing alcohol approach biases in alcohol dependent users (Wiers et al., 2013). Both substance use and obesity can be defined as disorders in which the salience of a specific type of reward (e.g., alcohol or energy-dense food) becomes exaggerated at the expense of other rewards (e.g. soft drinks or healthy foods) (Smith & Robbins, 2013). In the context of obesity, ABM has been applied to the eating domain in excess weight and healthy-weight university students using healthy foods as a direct alternative stimulus for unhealthy food cues.

The Implicit Association Training (IAT) comprises two types of images (unhealthy food versus healthy food/non-food related) and two conditions (avoidance- versus approach-related words). Participants in the Active Training condition (i.e. unhealthy food-avoidance) are instructed to associate unhealthy foods with avoidance-related words and healthy foods with approach-related words. The Active Control condition (e.g. unhealthy food approach) requires participants to associate unhealthy foods with approach-related words and healthy foods with avoidance-related words. The Approach Avoidance Training (AAT) comprises two types of images (unhealthy food versus healthy food/non-food related) and two conditions (avoidance-push versus approach-pull). Participants in the Active Training condition (i.e. unhealthy food-avoidance) are instructed to respond to images of unhealthy foods by making an avoidant movement (pushing the joystick) and to respond to healthy foods or non-food related images by making an approach movement (pulling the joystick). Active Control training conditions include (1) an equal number of approach and avoidance movements to both healthy and unhealthy food cues, and (2) approach of 90% of unhealthy food cues and avoidance of 90% of healthy food cues (i.e., unhealthy food approach).

4.1.2. Findings

Three studies retraining cognitive bias have utilized the training version of the approach-avoidance task (AAT) using joysticks to perform the approach and avoidance actions in university students. In all studies, the effect of the Active Training was relative to an Active Control comparison group. Becker and colleagues (Becker et al., 2015) have shown that the Active Training, does not improve implicit food preferences (measured by the Implicit Association Task), propensity to make healthy life-style choices (measured by an explicit preference task) or food choices (measured by a behavioral food choice task). Furthermore, two studies have investigated whether AAT-training using joysticks affects subsequent chocolate and muffin consumption, as measured by an ad-libitum eating taste test. Schumacher and colleagues (Schumacher et al., 2016) found that the Active Training (i.e. unhealthy food-avoidance) was associated with less consumption of chocolate muffin ad-libitum in an eating taste task. However, Dickson and colleagues (Dickson et al., 2016) found no evidence that the Active Training (i.e. unhealthy food-avoidance) reduces consumption of chocolate measured by an ad-libitum eating taste task. This inconsistency in results may be attributed to the increased power obtained by Schumacher and colleagues (Schumacher et al., 2016) from their larger sample size (N=120). Only one study has applied ABM training using the Implicit Association paradigm (Kemps et al., 2013). This study examined the effectiveness of a single session of ABM training for reducing craving in university students (Kemps et al., 2013). Findings showed that participants in the Active Training (i.e. unhealthy food-avoidance) reported less intense food craving indicated by a visual analogue scale than those in the Active Control condition (i.e. unhealthy food-approach), although this difference was not significant.

4.2. Attentional Bias Modification

4.2.1. Trainings

Attentional Bias Modification (AtBM) retrains attention towards healthy food cues and away from unhealthy food cues by consistently replacing healthy food images or words with dot probes (Modified Dot Probe Training). The Modified Dot Probe Training comprises two types of images or words (unhealthy food versus healthy food/non-food related) displayed on the computer screen. When the picture or word pair disappears, a dot probe is presented in the location of one of the previously presented images or words. Participants are instructed to identify the location of the probe as quickly as possible, by pressing the corresponding keys on the computer keyboard. Attention bias is manipulated by varying the location of dot probes for the two training conditions (i.e., Active Training and Active Control) and increasing the proportion of targets appearing at the location of the intended training bias. AtBM has been primarily applied to anxiety disorders aiming to reduce attentional bias to fearful facial expressions (Mogg & Bradley, 2016). In the context of obesity, AtBM has been applied to the eating domain in excess weight and healthy-weight university students owing to divert attention away from unhealthy foods cues, and directing attention instead towards healthy food cues.

For participants in the Active Training condition (i.e., healthy food-attention), dot probes consistently replace healthy food images, designed to direct attention to healthy food cues. For participants in the Active Control condition, dot probes consistently replace unhealthy food/non-food related images, designed to direct attention to unhealthy food cues or neutral stimuli.

4.2.2. Findings

Six studies have applied AtBM training using the Modified Dot Probe Paradigm. Two studies examined the effectiveness of a single session of AtBM training for reducing unhealthy eating in healthy-weight populations. Specifically, Kemps and colleagues (2014) found that the Active Training reduced chocolate consumption and craving, as measured by an ad-libitum eating taste task and a visual analogue scale, respectively (Kemps et al., 2014). Kakoschke and colleagues (2014) found that the Active Training, relative to Active Control, enhanced attentional bias towards healthy food cues, which in turn resulted in increased consumption of healthy snacks, as measured in an ad-libitum eating taste task (Kakoschke et al., 2014). Smith and Rieger (Smith and Rieger, 2009) also applied a single session among female healthy-weight participants, but their main goal was to assess the impact of different types of attentional biases (i.e., body shape related biases and healthy versus unhealthy food biases) on dietary restraint measured with a food choice task involving full fat versus low fat biscuits. Interestingly, they found a paradoxical effect – training bias towards unhealthy food induced higher proportion of low fat options, probably due to demand characteristics. Two other studies examined the effectiveness of a single session of active AtBM training compared to Standard Control conditions for reducing unhealthy eating behaviors, BMI and diet failure rate in university students with excess weight (Bazzaz et al., 2017; Hardman et al., 2013). Specifically, Hardman and colleagues found modest effects of active AtBM training on attentional bias to food images, and no effects on subjective levels of hunger and food intake, as measured by an analogue scale and a food preference test, respectively (Hardman et al., 2013). Bazzaz and colleagues (2017) found that the Active Training reduced BMI and diet failure rate, i.e., number of participants who quitted their diet from pretest to posttest and to the follow-up test (Bazzaz et al., 2017). Moderation analyses showed that high levels of restraint moderated the positive effect of the Active Training on BMI loss, particularly in those dieters with high levels of restraint. This finding suggests that AtBM training is particularly useful for excess weight dieters with restrained eating style. Kemps and colleagues (2015) examined the sustained effects of a single versus multiple sessions of AtBM training on chocolate consumption, as measured by an ad-libitum eating taste test (Kemps et al., 2015). Findings showed that AtBM training decreased chocolate consumption at a 24-h and 1-week follow-up, but only for those participants who received multiple sessions.

4.3. Implementation of Intentions

4.3.1. Trainings

Implementation of Intentions (II) utilizes the formation of intentions that reminds individuals of their dieting goal in response to food temptations to decrease consumption of unhealthy foods (Armitage, 2004). II are behavioral plans following an if-then structure creating a strong link between a specified situation and a response, making individuals selecting this response when entering the specified situation (e.g., If I am tempted to eat a burger when I am watching TV, I will think of dieting). II has been applied to the eating domain in excess weight and healthy-weight adults owing to improve dieting behavior through activation of a dieting goal.

In the Active Training condition of II, participants are told that forming a specific if-then plan will help them to eat less unhealthy food. Participants are instructed to make idiosyncratic II with regard to different eating occasions (i.e., breakfast, lunch, snacks during the day, dinner, snacks after dinner). For each eating occasion, participants are first instructed to think about the trigger of unhealthy food eating, i.e., the typical way in which such a situation unfolds (e.g., where, when and with whom they usually have unhealthy snacks), in a "if…" format (e.g., If I feel bored, I eat too much unhealthy snacks). Then, participants are instructed to think about an alternative behavior in a "then…" format (If [critical trigger], then [solution]). In the Active Control condition, participants are asked to make II on neutral events (e.g., taking it easy for five occasions during the five days of the week).

4.3.2. Findings

Three studies have applied II in the eating domain. The findings described below show the effect of the Active Training relative to the Active Control comparison group. Armitage (2004) examined the effectiveness of II for reducing fat intake measured by a food frequency questionnaire (Armitage, 2004). Findings showed that the II training reduced overall fat intake, saturated fat intake, and the proportion of energy derived from fat. Tam and colleagues (2010) examined whether matching II to individuals' regulatory orientation improved unhealthy snacking habits, as measured by the number of portions of healthy snacks compared to unhealthy snacks consumed over two subsequent days (Tam et al., 2010). Findings showed that individuals with weak unhealthy snacking habits consumed more healthy snacks when forming any type of II (regardless of match with their regulatory orientation), while participants with strong unhealthy snacking habits consumed more healthy snacks only when forming II that matched their regulatory orientations (promotion-focused or orientation-focused). Verhoeven and colleagues (2013) investigated the effectiveness of making a single versus multiple II for reducing unhealthy snacking habits, as measured by the Self-Report Habit Index (Verhoeven et al., 2013). Findings showed that a single plan successfully reduced unhealthy snacking habits, whereas formulating multiple II was ineffective. The negative effect of multiple II was due to interfering information while planning, rather than formulating multiple plans itself.

4.4. Response Inhibition

4.4.1. Trainings

Response inhibition (RI) training retrains prepotent motor responses associated with food cues by selectively pairing these cues with “No-go” signals. In the context of eating behaviour and obesity, RI training aims at improving the ability to inhibit prepotent response towards high calorie foods. The most typically used trainings include modified versions of the Go/No-go Task and the Stop Signal Task.

The Go/No-go training comprises two types of images (i.e. unhealthy food versus healthy food) and two conditions (go versus no-go). Participants are presented with a sequence of images and instructed to press a key when a go cue (e.g., letter “p”) and to withhold from responding when a no-go cue (e.g., letter “f”) are displayed on the picture. The images used in the training are usually a combination of unhealthy foods (e.g. snacks, potato chips or chocolate), healthy foods (e.g. vegetables, nuts, fruits) and filler images in order to mask the study purpose. In the Active Training condition, unhealthy food images are paired with no-go cues while healthy food images are paired with go cues. Active Control conditions include (1) unhealthy food images paired with go cues, and (2) food images and/or neutral images not consistently paired with signals.

In the Stop Signal Task training, the go cue is always presented first, and participants are instructed to push a button as quickly as possible, but to refrain their response when they hear a tone that serves as a stop signal. The images used in this training are a combination of unhealthy food (e.g. snacks, potato chips or chocolate), healthy food (e.g. vegetables, nuts, fruits) and non-food related images. In the Active Training condition, images of unhealthy food are paired in different proportions with stop signals (i.e. withhold from responding). Active Control conditions include (1) unhealthy food images paired with go signals, (2) food images not consistently paired with stop signals, (3) same task with no stop signals or instructions to ignore signals, and (4) general inhibition trainings (non-food specific). Standard Control conditions include (1) observing the same images without being required to respond, (2) doing other exercises, such as summarizing neutral stories, and (3) psychoeducation.

4.4.2. Findings

Seven studies have applied RI training using a modified version of the Go/No-Go Task. All studies compared the effect of the Active Training relative to the Active Control comparison group. In a series of studies, Veling and colleagues (2011; 2013a; 2013b) examined whether Go/No-Go training improves food choice and the amount of food consumed (as measured by a behavioral food choice task and an ad-libitum eating task, respectively), and whether appetite status and frequency of food consumption have an influence over training response among chronic dieters. Findings showed that a single session of active Go/No-Go training reduced the amount of sweets consumed and unhealthy food choices when participants' appetite was relatively high or when that food was usually consumed, and unhealthy food choice among high-appetite but not low-appetite chronic dieters. This reduction of unhealthy food choices was mediated by decreased evaluations, as measured by its attractiveness ratings, of the food previously associated with no-go cues (Veling et al., 2013a, 2013b, 2011). The other studies that have utilized Go/No-go training have been conducted in participants with healthy-weight and daily consumption of chocolate snacks or high levels of self-reported overeating. Two studies of the same research group (Houben and Jansen, 2015, 2011) examined whether a single session of Go/No-go training could reduce food desire and chocolate consumption, as measured by a visual analogue scale and an ad-libitum eating taste task, respectively. Findings showed that the Active Training significantly reduced desire to eat chocolate and subsequent chocolate intake. The only study involving multiple sessions utilized an online based Go/No-go training (Lawrence et al., 2015a). Findings showed that the Active Training effectively reduced weight, daily energy intake, ratings of liking of high energy-dense food after treatment, and self-reported weight at a six-month follow-up.

Four studies have applied RI training using a Stop Signal Training (SST). Studies using a single session have shown mixed results (Guerrieri et al., 2012; Houben, 2011; Lawrence et al., 2015b). Specifically, Houben (2011) examined if the efficacy of the training was influenced by individual differences in inhibitory control skills, measured with the Stop Signal Task. Findings showed that the Active Training was effective among participants with poor inhibitory control skills, whereas no training effect was shown among participants with high inhibitory control skills. Lawrence and colleagues (2015) examined the effect of training on high calorie food consumption, as measured by an ad-libitum eating taste task. Findings showed that the Active Training significantly reduced calorie intake compared to the Active Control (Lawrence et al., 2015b). Conversely, Guerrieri (2012) and Lawrence (2015b; Studies 2 and 3) found no evidence that the Active Training reduces food intake relative to Standard Control and Active Control conditions, respectively. Important modifications of the trainings employed in these two studies should be noted: (1) Guerrieri and colleagues (2012) utilized general inhibition training instead of food-specific inhibition training; and (2) Lawrence and colleagues (2015) utilized a food inhibition training in which unhealthy foods were associated with stop signals only in 50% of the trials.

In a series of studies, Allom and Mullan (2015) examined the effect of 10 daily sessions of Stop Signal online training on BMI, and whether vulnerability to depletion, as measured by the Stroop Interference task, mediates the training effect (Allom and Mullan, 2015). Findings showed that the Active Training, relative to Active Control conditions, was associated with a significant reduction in self-reported BMI, and BMI changes were mediated by changes in vulnerability to depletion. However, the training effect on BMI was not replicated in their subsequent study, in which weight and height assessments were objectively measured (Allom and Mullan, 2015). Adams and colleagues (2017) compared the effectiveness of SST and Go/No-Go training for reducing food consumption in restrained eaters with frequent cravings, as measured by an ad libitum eating task (Adams et al., 2017). This series of studies further explored whether the effect of training was due to stimulus devaluation (as measured by an implicit association test, SC-IAT) and stimulus-specific associations (as measured by calorie consumption of different foods on the ad libitum eating task) for reducing food consumption. Although Go/No-Go training had greater effects on reducing unhealthy food consumption compared to SST, overall results showed no effect of both Active Training conditions (SST and Go/No-Go).

4.5. Episodic Future Thinking

4.5.1. Trainings

Episodic Future Thinking (EFT) trains focus on long-term goals by strengthening the mental representation of future events through imagery exercises (Atance and O'Neill, 2001;

Peters and Büchel, 2010). The imagery exercises involve mental projections of future events based on specific and detailed personal goals. In the context of obesity, EFT training has been applied to the food decision-making domain in individuals with healthy-weight and excess weight aiming to make food decisions in the present congruent with long-term health goals (Daniel et al., 2013a).

EFT training is based on the development of customized cues for each participant that will later act as facilitators of episodic-thinking (Peters and Büchel, 2010). Specifically, EFT training in the eating domain facilitates episodic-thinking in situations related to eating behaviors. The cues are generated by matching participant's health-related goals (e.g., practicing sport three times per week) with future events expected to occur in the next days/weeks (e.g., go to a dinner next Saturday). The format of the cues eliciting episodic thinking are similar to "next Saturday, I will go out to dinner with my partner and I will feel proud and happy about achieving my goal of going to gym". In order to facilitate a vivid representation of the events, participants are required to contemplate as many details of the event as possible (i.e., contextual who, when, what, where). In the Active Training conditions, episodic cues are based on future planned events (EFT) based on eating behaviors. Active Control conditions include (1) general EFT cues (not related to eating behavior), and (2) episodic cues based on the recall of events (ERT) either with general or food-related content. The Standard Control condition consists of a non-episodic memory related task.

4.5.2. Findings

Four studies have applied EFT training in the eating domain. Two of these studies examined whether food-related EFT training was more effective than non-food related EFT training and/or episodic recall (past-oriented) training (ERT) in promoting healthier dietary choices among female university students with healthy-weight. Specifically, Vartanian and colleagues (2016) found a positive effect of both food-related EFT and ERT trainings on calorie intake compared to active non-food related conditions and Standard Control (Vartanian et al., 2016). Conversely, Dassen and colleagues (2016) found that only active food-related EFT training, relative to Active Control conditions, was associated with less amount of calorie consumption, as measured by an ad-libitum eating taste test. Moreover, Dassen and colleagues (2016) also examined whether discounting rates (i.e., preference for immediate versus delayed rewards) measured by a Monetary Choice Questionnaire (Kirby et al., 1999) could be improved through EFT training (Dassen et al., 2016). Findings showed that EFT reduced discounting of the future compared to ERT, independently of the content (general or food-related) of the training. However, no association was observed between discount rate and caloric intake.

The other two studies utilizing EFT training have been conducted in female participants with excess weight. Daniel and colleagues (2013a) examined the efficacy of EFT training for reducing impulsivity and energy intake, as measured by a delay discounting task and an ad libitum eating task, respectively (Daniel et al., 2013a). Findings showed that EFT training significantly reduced participant's delay discounting and energy intake compared to the Active Control condition. O'Neill and colleagues (2016) examined EFT training in a natural environment (i.e., feeding session conducted in a real food court) in order to identify the suitability of a smartphone based intervention to reduce calorie and macronutrient intake, as measured by an ad libitum eating task. Findings showed that the Active Training significantly reduced the total amount of calorie consumption and the percentage of calories from fat, and increased the percentage of calories from protein compared to the Active Control condition.

4.6. Working Memory

4.6.1. Trainings

Working memory training (WMT) aims to strengthen information maintenance, manipulation and updating, through progressively challenging mental exercises (e.g. letter and digit strings, visual searches, mental arithmetic tasks, N-back tasks) (von Bastian and Oberauer, 2014). In the context of obesity, WMT has been utilized owing to the improvement of cognitive control functions via strengthening of WM.

The Active Training strengthens the maintenance and manipulation components of working memory via verbal and visual exercises with progressive difficulty adjustment. Active Training includes three different tasks: (1) visuospatial WM task (i.e., a sequence of squares changes in color, and participants are instructed to reproduce the order in which the sequence was produced), (2) backward digit span task (i.e., participants are instructed to reproduce a sequence of a previously presented numbers in reverse order), and (3) a letter span task (i.e., participants are presented with two letters at a time, asked to read the letters aloud, and then recall letters in the same sequence). The Active Control group completed a modified training with the same exercises remaining on the initial easy level during all treatment.

4.6.2. Findings

Only one study has applied WMT in individuals with excess weight. Houben and colleagues (2016) examined the effectiveness of an online training to reduce body weight and amount of food intake, as measured by an ad libitum eating task (Houben et al., 2016). The training consisted of 20-25 internet-based sessions delivered on a daily basis. Overall, the Active Training did not reduce food intake nor body weight in any of the follow up assessments. However, among participants with strong dietary restraint goals, WMT effectively reduced food intake. The Active Training, compared to the Active Control condition, had positive effects on eating related symptomatology (i.e., decreased eating and shape concerns) post-treatment and at the follow-up assessment. Emotional eating was significantly reduced in the Active Training group, and the effects were still present at the follow-up assessment and one month later.

4.7. Combined interventions

4.7.1. Findings

Four studies compared the effectiveness of II training plus other interventions targeting impulsive processes of eating behavior (e.g., Go/No-Go, Stop Signal, Cue-Monitoring and Behavioral Intention) for reducing BMI and unhealthy eating patterns. Specifically, Veling and colleagues (2014) found that Active II and Go/No-Go trainings facilitated weight loss compared to Standard Control condition (i.e., Neutral Go/No-Go and Neutral II) and that combining both active trainings resulted in a larger therapeutic effect. II enhanced weight loss particularly among people with a strong dieting goal whereas Go/No-Go was primarily effective among dieters with a relatively high BMI (Veling et al., 2014). Koningsbruggen and colleagues (2014) found that both Active II and Go/No-Go trainings, compared to Standard Control (i.e., Neutral Go/No-Go and Neutral II), reduced the amount of palatable food selected in a sweet-shop-like environment and a computerized snack dispenser (van Koningsbruggen et al., 2014). However, combining the interventions did not lead to additive effects. Verhoeven and colleagues (2014) found that cue-monitoring either or not combined with II reduced unhealthy snacking compared to Standard Control (Verhoeven et al., 2014). With cue-monitoring, Verhoeven and colleagues (2014) referred to closely observing unhealthy snack intake in relation to specific situational and motivational circumstances, thereby reflecting upon the critical cues triggering the unwanted responses (Verhoeven et al., 2014). Forming II did not reduce snacking frequency. That is, according to this study, cue-monitoring suffices to reduce unhealthy snacking, without adding benefit from planning. Benyamini and colleagues (2013) found that II and Behavioral Intentions conditions were associated with 40% more weight loss than the Standard Control condition (Benyamini et al., 2013). Weight loss goals showed to be an important moderator of II effects, with those with higher initial diet goals getting the greater benefits.

Two studies examined the effects of Response Inhibition (RI) training combined with other interventions. Specifically, Forman and colleagues (2016) examined the independent and combined effects of RI training and Mindful Decision-making Training (MDT) on snack consumption (as measured by an Ecological Momentary Assessment) in university students with healthy-weight and excess weight and with daily consumption of unhealthy snacks (Forman et al., 2016). The moderation effect of dietary disinhibition over the training effectiveness (as measured by the disinhibition subscale of the Eating Inventory and the emotional eating subscale of the Dutch Eating Behaviour Questionnaire) was also examined. Findings showed that Stop Signal Training, Mindful Decision-making Training, and the combined treatment all produced significant reductions in snack consumption. The effect of MDT was consistent across levels of trait emotional eating whereas the benefit of Stop Signal Training was observed only at lower levels of emotional eating. Kakosche and colleagues (2017) explored the independent and combined effects of ABM and RI on implicit evaluations, food choice and food consumption (as measured by SC-IAT, a food-choice task and an ad-libitum eating test, respectively) in university students with healthy-weight (Kakoschke et al., 2017). Results showed that combining both ABM and RI trainings results on more negative implicit evaluations of unhealthy food. However, food intake was not different across training conditions. In regards to food choice, active ABM training was associated with higher likelihood of choosing a healthy snack, but combining trainings did not lead to additional benefits.

4.8. Summary of Cognitive Training studies

Table 2 summarizes the effects of the cognitive trainings reviewed on the nominated outcome measures for people with healthy weight and those with overweight and obesity.

Three cognitive trainings have shown to significantly reduce BMI in people with overweight and obesity: Response Inhibition (Lawrence et al., 2015a; Veling et al., 2014), Implementation of Intentions (Benyamini et al., 2013) and Attentional Bias Modification (Bazzaz et al., 2017). In all cases, beneficial effects have been found using multiple training sessions (between 4 and 10). These three trainings, along with Episodic Future Thinking, are also efficacious for reducing consumption of energy-dense foods, food cravings and the desire to eat in community samples including people with healthy and excess weight (Armitage, 2004; Daniel et al., 2013b; Dassen et al., 2016; Forman et al., 2016; Houben, 2011; Houben and Jansen, 2015; Kemps et al., 2015, 2014; Lawrence et al., 2015b; O'Neill et al., 2016; Tam et al., 2010; van Koningsbruggen et al., 2014; Vartanian et al., 2016; Veling et al., 2011; Verhoeven et al., 2014). The effect size of the interventions is small to moderate.

Positive effects of Response Inhibition training have been consistently replicated. The training has shown to be more useful among participants with high levels of appetite and dietary restraint levels, and low levels of inhibitory control (Adams et al., 2017). In addition, Go/No-Go trainings have shown to be more effective for reducing BMI and energy-dense food intake than SST trainings (Adams et al., 2017; Veling et al., 2011). This difference suggests that cognitive rather than motor inhibition is critical to change diet and achieve weight loss. The Implementation of Intentions approach has shown to be particularly effective among goal-driven individuals, as those participants with stronger pre-treatment weight loss goals get the greatest benefits of this intervention (Benyamini et al., 2013). Attentional Bias Modification (AtBM) training is a promising therapy for reducing unhealthy eating (Schumacher et al., 2016), but more studies are warranted to examine its effectiveness in individuals with excess weight (Bazzaz et al., 2017). Dose effectiveness studies have shown the need for multiple training sessions to yield sustained improvement in unhealthy eating patterns (Kemps et al., 2015).

A single session of Episodic Future Thinking has been shown to be efficacious to reduce energy-dense food intake in individuals with excess weight and healthy-weight (Vartanian et al., 2016). However, the extent to which this intervention has lasting effects in everyday food intake and in eating habits still remains unexplored. Although Approach Bias Modification and Working Memory trainings reduce unhealthy eating in people with normal weight, they have not shown significant effects on weight loss. A single session of Approach Bias Modification (ABM), albeit effective to change alcohol preferences in hazardous drinkers, is not enough to influence individual's preference for energy-dense food (Wiers et al., 2010). Most alcohol ABM studies have shown that between 4 and 12 20 min training sessions are necessary to reduce alcohol approach bias (Verdejo-Garcia, 2016). Working memory (WM) training is particularly efficacious for reducing energy-dense food intake among those individuals with strong dietary restraint goals (Houben et al., 2016). However, this evidence is based in a single study. More research is needed to replicate these findings, as well as to examine the effectiveness of WM training on BMI reduction.

The mean quality of the cognitive training studies was 10.21 (SD=1.17) on the Thompson scale (ranging 0-13), suggesting moderately high quality and little variability across studies. Detailed assessments are provided in Table S1 of the Supplementary Material. The main detractions from quality were due to unclear description of inclusion and exclusion criteria and lack of blinding.

5. Neuromodulation findings, classified by intervention

Table 3 summarizes the design, participants, interventions and main findings of the studies reviewed in this section.

5.1. Non-invasive brain stimulation

Non-invasive brain stimulation techniques produce changes in neural activity via a safe, external, non-surgical manipulation. Repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) are the most commonly used techniques (Hallett, 2007; Nitsche et al., 2008). Both techniques exert small electrical currents in the brain that cause alterations in neuronal firing, and results in excitatory or inhibitory effects depending on the stimulation frequency. Both rTMS and tDCS have been primarily applied to patients with depression reporting successful enhancement of mood (Shin et al., 2015; Wassermann and Zimmermann, 2012). In recent years, their scope has been extended, and they have shown promising effects in other psychiatric and neurological disorders, such as schizophrenia (Agarwal et al., 2013; Cole et al., 2015), dementia (Elder and Taylor, 2014), substance use disorders (Kekic et al., 2016a) and eating disorders, such as anorexia nervosa and bulimia nervosa (McClelland et al., 2013; Sauvaget et al., 2015). In the context of obesity, non-invasive brain stimulation has been applied to inhibit the neural activity associated with craving responses, such as the hyperactivation of the orbitofrontal cortex and the anterior cingulate cortex, and to enhance the activity of regions involved in cognitive control, such as the dorsolateral prefrontal (Val-Laillet et al., 2015).

5.1.1. Repetitive Transcranial Magnetic Stimulation (rTMS)

5.1.1.1. Technique and Stimulation Protocol

TMS modulates the underlying cerebral cortex and neural activity beneath the site of stimulation via an electrode field generated by a coil (Wassermann and Zimmermann, 2012). Delivery of a single pulse enables examination of cortical excitability whereas the delivery of multiple pulses over a short period, known as repetitive TMS (rTMS), induces longer lasting neural effects (McClelland et al., 2013).

In the context of obesity, the Active Stimulation condition utilizes rTMS (10Hz) delivered over the left dorsolateral PFC (DLPFC) comprising either 1000 pulses over 20 min (Uher et al., 2005) or 3000 pulses over 15 minutes (Barth et al., 2011). The Standard Control conditions consist of rTMS aiming to replicate the sensation of magnetic stimulation without deep nerve activation.

5.1.1.2. Findings

rTMS has been applied in two studies among women with strong, frequent food cravings who had both healthy weight and excess weight. These studies examined the effectiveness of a single session of rTMS over the left DLPFC to reduce cue-induced food craving, indicated by participants urge to eat (Barth et al., 2011; Uher et al., 2005) and the energy value of the food eaten in an ad libitum eating task (Uher et al., 2005). In the study carried by Uher and colleagues (2015), exposure to real food was used to induce craving. Findings showed that food craving remained stable after the Active Stimulation, whereas it was increased after Standard Control. However, food consumption in the ad libitum eating task did not differ between the Active Stimulation and the Standard Control conditions. In the study carried by Barth and colleagues (2011), the Standard Control condition created a similar sensation of discomfort to rTMS with no effect on cortical activity. Findings showed no difference in food craving ratings between the Active Stimulation and the Standard Control condition.

5.1.2. Transcranial Direct Current Stimulation (tDCS)

5.1.2.1. Technique and Stimulation Protocol

Transcranial direct stimulation (tDCS) applies a weak direct current from one electrode (excitatory; anode) to another (inhibitory; cathode). Approximately 50% of the current delivered by tDCS penetrates the scalp and can raise or decrease the resting membrane potential of neurons in underlying areas (anodal or cathodal tDCS stimulation, respectively), causing changes in spontaneous firing. Excitation/inhibition protocol parameters are achieved by exchanging the positions of the electrodes between left and right hemispheres (McClelland et al., 2013). The existing studies have applied tDCS protocols targeting the DLPFC aiming to modulate food cravings in individuals with healthy-weight and excess weight. In the Active Stimulation, real tDCS is delivered whereas in the Standard Control condition the stimulation is turned off after few seconds.

5.1.2.2. Findings

Non-invasive neuromodulation tDCS trainings have been applied in eight studies mainly involving women with healthy weight, selected according to frequency of food cravings. The findings described below are always relative to Control condition. Studies using a single session of tDCS over the DLPFC have shown overall positive effects on craving, as measured by food craving questionnaires (Fregni et al., 2008; Lapenta et al., 2014; Montenegro et al., 2012), as well as craving specific to sweets (Goldman et al., 2011; Kekic et al., 2014) and carbohydrates (Goldman et al., 2011).

With regard to the effects of tDCS on food consumption measured by ad libitum eating tasks findings have shown mixed results. Specifically, two studies reported that both anodal stimulation of the right DLPFC (Fregni et al., 2008; Lapenta et al., 2014) and the left DLPFC (Fregni et al., 2008) reduced calorie intake (Fregni et al., 2008; Lapenta et al., 2014) whereas other two studies reported no changes on food consumption after anodal stimulation of the right DLPFC (Goldman et al., 2011; Kekic et al., 2014). In addition, Montenegro and colleagues (2012) utilized tDCS stimulation over the left DLPFC along with aerobic exercise to examine whether the combined treatment has an impact on hunger, satiety and desire to eat sensations in individuals with excess weight. Findings showed superior effects of the combined treatment in suppressing desire to eat compared to either tDCS or exercise alone.

To date, three studies have involved multiple training sessions and both have reported positive effects. Specifically, in a crossover study, Jauch-Chara and colleagues examined he effects of 8 daily 20 min sessions of Active Stimulation over the right DLPFC on an ad libitum task in a male sample (Jauch-Chara et al., 2014). Findings showed a significant reduction of total calorie consumption after tDCS Active stimulation compared to Standard Control. Further analysis of macronutrient intake revealed that the decreased total calorie consumption was particularly attributable to a decrease in carbohydrates consumption. Gluck and colleagues (2015) conducted training consisting of 3 daily 40-minutes sessions on a sample of obese participants. Findings showed that patients receiving Active stimulation over the left DLPFC consumed significantly less daily calories from soda and fat than those undergoing Standard Control condition. Moreover, percent weight change after the 3 day ad-libitum intake period and the 9 day inpatient period was greater after anodal rather than cathodal condition, while participants undergoing Standard Control condition on both occasions did not experience any change on body weight (Gluck et al., 2015). Ljubisavljevic and colleagues (Ljubisavljevic et al., 2016) examined the immediate and long-term effects of tDCS over the right DLPFC on food craving in a sample involving healthy-weight male and females. Active Training consisted of 5 daily 20 min sessions whereas Control involved a first active 20 min session followed by 4 Standard Control sessions with no current flow. Findings showed that a single Active session had immediate positive effects on food craving, although the five sessions were needed to reduce habitual craving experiences.

5.2. Deep Brain Stimulation (DBS)

5.2.1. Technique

Deep brain stimulation (DBS) is an invasive technique aimed to modulate the activity of dysfunctional brain circuits through the delivery of direct electrical stimulation signals (Karas et al., 2013). These signals are given by a pair of electrodes directly implanted in specific brain regions through surgery and controlled by a generator (neuroestimulator) usually implanted in the chest. DBS was first developed as a treatment for Parkinson’s disease and in last years it has been also applied on an experimental basis as a treatment for some psychiatric disorders such as depression, Obsessive Compulsive Disorder and Substance Use

Disorders proving to be a safe technique and reporting successful results (Coenen et al., 2015; Karas et al., 2013; Vanegas and Zaghloul, 2015). In the context of obesity, deep brain stimulation has been applied to the eating domain primarily aiming to regulate feeding behavior via modulation of homeostatic (i.e., lateral hypothalamus area, LH) and reward circuits (i.e., nucleus accumbens, NAcc).

5.2.2. Findings

Only two studies have applied DBS in the eating domain. It has been applied to patients with severe obesity, with the aim of restoring dysfunctional neural activity in the brain's feeding and satiety centers (Ho et al., 2015). In a case series, Whiting and colleagues placed DBS electrodes bilaterally in the lateral hypothalamic area (LHA) in three treatment-resistant patients with morbid obesity (Whiting et al., 2013). Findings suggested that continuous monopolar DBS over the LHA in these patients was a safe method and, after a mean follow-up of 35 months, two of the three patients showed significant weight loss while the other patient maintained a stable weight. Harat and colleagues (2016) applied DBS bilaterally over the nucleus accumbens on a single case of a 19 years old female with "hypothalamic obesity" (e.g., complication in some survivors of brain tumors resulting in a damaged hypothalamus) exhibiting craving for food and drugs, aiming to modulate immediate reward circuits (Harat et al., 2016). After a 14-month follow-up, the patient showed a significant weight loss and reported no feelings of increased appetite nor increased need for food.

5.3. Neurofeedback

5.3.1 Technique

Neurofeedback using functional Magnetic Resonance Imaging (fMRI) or electroencephalography (EEG) trains individuals to voluntarily regulate their brain activity in response to real-time information about their brain activity (Gruzelier, 2014; Weiskopf, 2012). The level of neural activity in a target area is fed-back to the individual using a brain-computer interface, and this provides continuously updated information about their success in regulating their neural activity, which can aid the modification of mental states and behavior (Gruzelier, 2014). In the context of eating behaviour and obesity, neurofeedback has been used to down-regulate brain activity during exposure to appetizing food.

5.3.2. Findings

Only two studies have applied Neurofeedback training in the eating domain. Specifically, Schmidt et al. (2015) used a cue exposure based EEG neurofeedback protocol to target overeating episodes, as measured by the Eating Disorder Examination Questionnaire, in a sub-clinical sample of female restrained eaters (Schmidt and Martin, 2015). At post-treatment (10 sessions in 6 weeks), the Active Training was associated with significant reduction of weekly overeating episodes, compared to the waiting list control group. This beneficial effect remained stable at 3 month follow-up. Ihssen et al. (2016) used an Approach Bias Modification (ABM) based fMRI neurofeedback protocol to target hunger, measured by a subjective questionnaire, in adults with healthy weight and excess weight (Ihssen et al., 2016). Findings showed hunger reductions after neurofeedback over brain regions importantly involved in food valuation (i.e., the amygdala, the insula and the medial prefrontal cortex) and an association between the degree of amygdala activity relaxation and hunger reduction.

5.4. Summary of Neuromodulation studies

Table 4 summarizes the effects of the brain stimulation approaches reviewed on the nominated outcome measures for people with healthy weight and those with overweight and obesity. Studies utilizing rTMS have shown that a single session of this technique is not efficacious to reduce food craving or energy-dense food intake (Barth et al., 2011; Uher et al., 2005). Conversely, studies utilizing a single session of tDCS over the right (Goldman et al., 2011; Kekic et al., 2014; Lapenta et al., 2014) or left DLPFC (Montenegro et al., 2012) have shown that this technique is efficacious for reducing food cravings in individuals with healthy and excess weight. Multiple (but not single) sessions of tDCS have shown to reduce energy intake, especially carbohydrates (Jauch-Chara et al., 2014). Multiple sessions are also needed to achieve sustained changes in craving (Ljubisavljevic et al., 2016). The combination of tDCS and aerobic exercise is more efficacious for reducing the desire to eat than tDCS alone (Montenegro et al., 2012).

The limited evidence of DBS over the nucleus accumbens (NAcc) and the hypothalamus (LHA) indicates that this invasive technique could be a promising therapy for achieving weight loss and reducing food craving in individuals with morbid obesity who are resistant to less invasive treatments (Harat et al., 2016). Emerging studies on neurofeedback suggest that this is a promising approach. ABM-based neurofeedback training has been shown to reduce hunger via down-regulation of activity in brain regions involved in reward valuation (Ihssen et al., 2016). Moreover, cue-exposure based EEG neurofeedback training has been shown to reduce the frequency of overeating episodes and food craving post-treatment and at a 3-month follow up in individuals with excess weight and healthy-weight (Schmidt and Martin, 2015).

The mean quality of the neuromodulation studies was 12.25 (SD=1.48) on the Thompson scale (ranging 0-13), suggesting high quality and little variability across studies. Detailed assessments are provided in Table S2 of the Supplementary Material. The main detractions from quality were due to lack of experimenters blinding.

6. Neurocognitive mechanisms relevant to the efficacy of cognitive and neuromodulation strategies for obesity

We are only beginning to learn about the neurocognitive mechanisms that underlie the effects of cognitive and neuromodulation strategies in the context of unhealthy eating habits and obesity. In the following paragraphs, we discuss preliminary insights from cognitive training and neuromodulation studies, as well as combined insights from both literatures.

In the area of cognitive training, Implementation of Intentions and Inhibitory Control were the most effective approaches for reducing unhealthy diet and weight in people with overweight and obesity. Implementation of Intentions has been proposed to work via a double mechanism: disruption of the stimulus-response schemas that underpin unhealthy eating habits, and creation of action plans that state when, where and which goal-driven behaviors need to be implemented (Wood and Rünger, 2016). This strategy can be used to increase self-control over eating habits and to promote healthier choices (Lally and Gardner, 2013). The Implementation of Intentions training is sensitive to individual differences in the strength of individual's dietary goals, and hence people with stronger pre-commitment get the greatest benefits of this program (Benyamini et al., 2013). This is consistent with the goal-conflict theory of eating behavior, which posits that dieting reminders are effective to facilitate compliance in individuals who have strong dietary goals (Briki, 2016; Stroebe et al., 2013). It is also interesting to note that Implementation of Intentions worked better with single versus multiple plans, due to competing interference in the latter condition (Verhoeven et al., 2013). This phenomenon speaks to the relevance of combining Implementation of Intentions with other interventions that can boost cognitive control skills (van Konningsbruggen et al., 2014; Veling et al., 2014).

Within Response Inhibition trainings, Go/No-Go training has been shown to be more effective than Stop Signal Training to reduce food intake and unhealthy food choices, and facilitate weight loss at short and long-term. Go/No-Go inhibition training is especially effective for people who are already trying to restrict food intake to maintain or achieve a healthy weight, but are generally unsuccessful at their dieting attempts. Three mechanisms have been proposed to explain the effectiveness of Go/No-Go training: (1) top-down inhibitory control over food-related responses, (2) creation of direct food item-stop associations, that is, automatic inhibition, and (3) reduction of hedonic or motivational value of food items (Houben and Jansen, 2015; Stice et al., 2016; Veling et al., 2017). However, existing studies have not yet determined which of the above proposed mechanisms best accounts for the effects of Go/No-Go training, as only a minority of these studies have investigated these mechanisms as potential moderators of training effects on food intake, unhealthy food choice, and weight loss.

Attentional Bias Modification (AtBM) and Episodic Future Thinking (EFT) are promising approaches in need of more research. Multiple sessions of AtBM can modify biases towards unhealthy foods, and there is preliminary evidence of translation into weight loss outcomes, possibly via changes in diet (Bazzaz et al., 2017). EFT can boost preference for delayed rewards (e.g., health goals) by strengthening cognitive representations of future states (Benoit et al., 2011; Peters and Büchel, 2010). Accordingly, EFT training reduces delay discounting rates in individuals with excess weight (Daniel et al., 2013a). A recent study has shown that EFT also reduces consumption of unhealthy foods, but not via reduced delay discounting (Dassen et al., 2016). Therefore, more studies are needed to reveal the mechanism underlying the effects of EFT on food intake.

An improved understanding of the cognitive mechanisms that underlie the effects of successful cognitive training in obesity may also inform the use of neuromodulation strategies, such as transcranial Direct Current Stimulation (tDCS), repetitive Transcranial Magnetic Stimulation (rTMS), Neurofeedback and Deep Brain Stimulation (DBS). Direct Current Stimulation (tDCS) has been found to improve inhibitory control skills in individuals with excess weight (Lapenta et al., 2014), and reduce cognitive biases towards alcohol cues in people with alcohol dependence (Uyl et al., 2017). The underlying mechanism is that stimulating DLPFC activity enhances cognitive control processes and attenuate the activity of automatic processes that drive food craving (Val-Laillet et al., 2015). There is evidence suggesting that the underlying DLPFC-dependent mechanisms may involve changes in reward valuation (Camus et al., 2009), attentional biases (Fregni et al., 2008) and enhanced cognitive-control abilities (Lapenta et al., 2014; Lowe et al., 2014). Self-regulatory abilities and cognitive control have been widely associated with DLPFC operations, and therefore, it is plausible that stimulating this brain region results in reduced unhealthy eating behaviors (Hare et al., 2009; Kober et al., 2010; Ridderinkhof et al., 2004). The alternative, probably complementary approach is to tame impulsive responses. In this vein, Ihssen and colleagues (2016) showed that neurofeedback-induced down-regulation of regions of the impulsive system (e.g., amygdala and insula) shifts approach biases towards healthy food.

The combined insights of cognitive training and neuromodulation studies suggest two cognitive/neural therapeutic pathways. One involves strengthening planning, cognitive control and neuroplasticity in lateral prefrontal systems, and is illustrated by the success of Implementation of Intentions and Response Inhibition trainings and DLPFC stimulation (Benyamini et al., 2013; Gluck et al., 2015; Veling et al., 2014). A second pathway involves retuning of motivational/impulsive biases and relaxation of reward-related reactivity in medial prefrontal, limbic and homeostatic systems, as illustrated by the promising findings of Attentional Bias Modification, Episodic Future Thinking and Neurofeedback, as well as hypothalamic/accumbens stimulation in severe obesity (Bazzaz et al., 2017; Harat et al., 2016; O'Neill et al., 2016; Whiting et al., 2013). The usefulness of these pathways is also reinforced by the positive findings of combined interventions that include two approaches tapping into the same mechanism, such as Implementation of Intentions + Response Inhibition (pathway 1) (van Konningsbruggen et al., 2014; Veling et al., 2014) or Approach Bias Modification + Neurofeedback over the medial prefrontal/limbic system (pathway 2) (Ihssen et al., 2016).

Our interpretations should nonetheless be appraised in the context of several methodological considerations to the literature included in this review. The main limitations of existing studies are the limited number of randomized controlled trials, the predominance of single-session versus multiple-session studies, the lack of representativeness in populations studied (existing studies largely involved female undergraduates), and the lack of systematic replication of findings across different treatment modalities. Overall, all treatment modalities would benefit from more rigorous clinical trial studies with clinical samples. These trials should examine potential mediators of treatment effectiveness, and determine if the treatments have significant effects on obesity and eating behaviors. Another important direction for future research would be to investigate factors that amplify the effects of treatment response, which would allow clinicians to target the populations most likely to benefit from each treatment modality. It may also be relevant to evaluate whether adding cognitive and neuromodulation strategies to extant weight loss interventions increases their efficacy.

7. Concluding remarks

The existing literature shows promising results of cognitive training and neuromodulation approaches in the context of eating behaviors and obesity. Both interventions are generally efficacious to reduce unhealthy eating behaviors in the short-term. Overall, the rationale for utilizing cognitive and neuromodulation approaches in the treatment of obesity is becoming stronger. However, the optimal training approach and administration protocol to achieve clinically meaningful outcomes (e.g., sustained changes in diet, weight loss) remains unclear. To date, a wide range of cognitive training protocols have been used involving different frequency, intensity, duration, and target domains. The same applies to neuromodulation studies, which have used a variety of stimulation sites and parameters. Most of the available studies provide proofs-of-concept evidence, and have been designed to provide preliminary evidence of efficacy and/or to interrogate possible cognitive/neural mechanisms, rather than testing and yielding standardized protocols for clinical application.

In order to examine the potential application of both cognitive and neuromodulation approaches to modify unhealthy eating, testing the sustainability of the effects of these interventions is also crucial. With the exception of few studies that included follow-up assessments one week to six months after the training, the remaining studies only evaluated acute effects immediately after training (Benyamini et al., 2013; Kekic et al., 2016b; Kemps et al., 2015; Lawrence et al., 2015a; Ljubisavljevic et al., 2016; Schmidt and Martin, 2015). Given the positive results of cognitive training approaches on clinical outcomes in other disorders (e.g., abstinence rates in addiction (Kekic et al., 2016b; Keshavan et al., 2014; Temel et al., 2012; Verdejo-Garcia, 2016; Wiers et al., 2011), more clinical research is needed in the area of obesity and eating disorders.

This review focused on strategies that tap into the cognitive and brain mechanisms that underpin unhealthy eating habits. Given that cognitive training and neuromodulation strategies both affect neuroplasticity, combined interventions may generate a synergistic effect (Val-Laillet et al., 2015). In this vein, a growing body of studies are assessing whether combining both approaches could further enhance cognitive performance on a given domain compared to a single approach alone. Available studies have mainly focused on memory and working memory enhancement using cognitive training together with tDCS. Results suggest that this combined approach can produce better outcomes, indicated by improved performance on the trained tasks (near transfer) and generalisation to other cognitive domains, including strengthened cognitive control (far transfer), as well as longer lasting effects on neuroplasticity (Au et al., 2016; Looi et al., 2016; Purves et al., 2001; Richmond et al., 2014). Relevant to the eating domain, the study of Ditye et al (2012) found that tDCS combined with inhibitory control training (SST) was effective for improving the ability to inhibit responses, producing a steeper learning slope in comparison to cognitive training alone (Ditye et al., 2012).

In sum, since existing studies show that multiple training/stimulation sessions are needed to achieve sustained changes in unhealthy eating, we advocate for more research on intensive training and neuromodulation interventions. It is also important to explore the boosting and synergistic effects of combined approaches. Future studies need to improve the methodological design, adopting current standards for clinical trials (Chan et al., 2013a, 2013b), and change the focus from healthy samples and short-term outcomes into clinical populations and meaningful, long-term outcomes.

Conflicts of interest

All authors declare no conflicts of interest.

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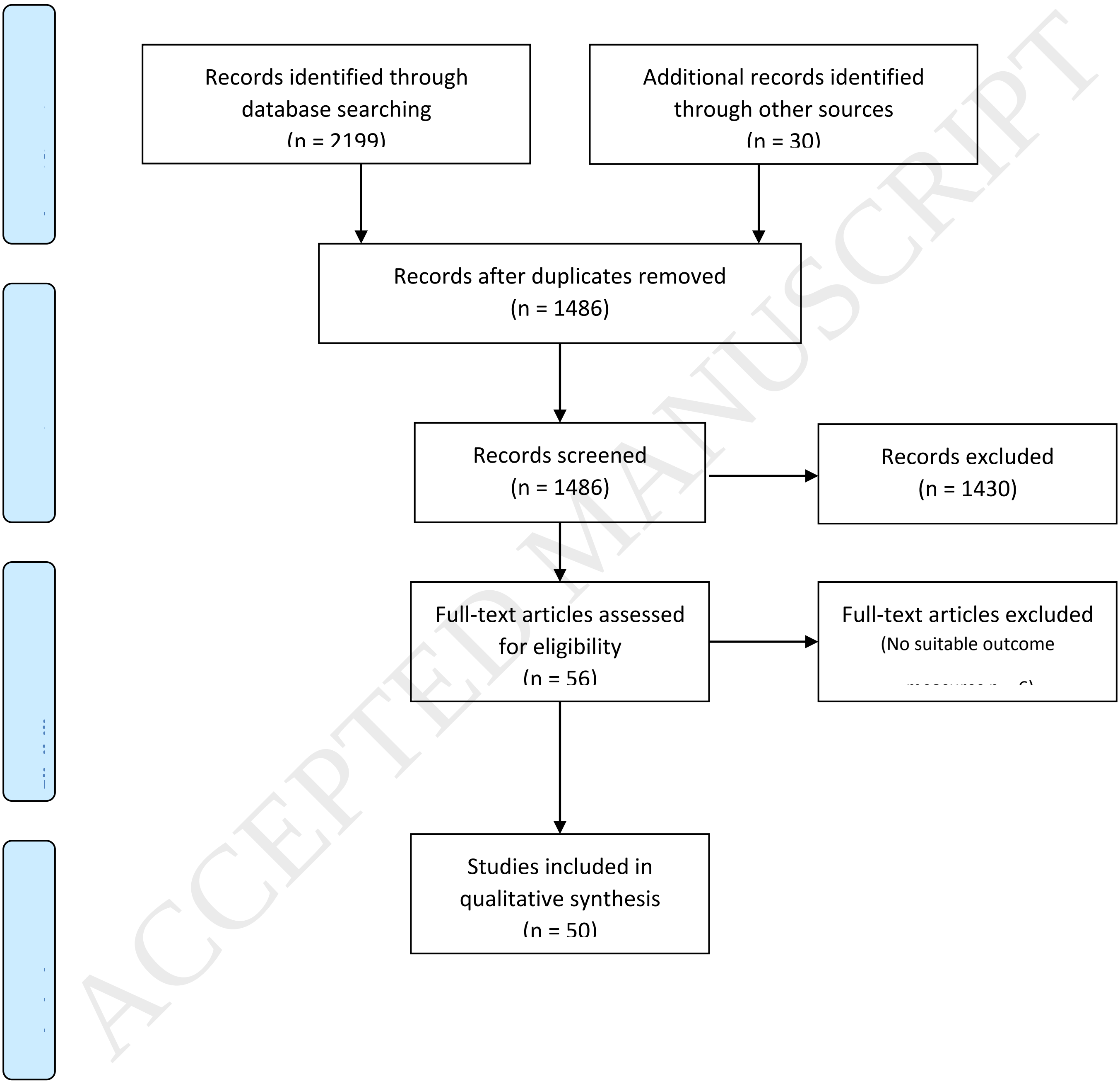

Figure .1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram—Cognitive and neuromodulation studies.

Table 1. Cognitive training studies aiming to modify eating behaviors.

Study	Training	Design	Participants	Main outcomes	Main findings	Effect size (Cohen's *d*)
Forman et al. (2016)	Stop Signal task(SST) and Mindful decision-making (MD) Format: computerized Delivery: Single dose SST: 20 min; MD: 60 min; Psychoeducation: 60 min Active mechanism: Response inhibition	Randomised Between groups Active Training: (1) MDT; (2) SST; (3) MDT and SST. Standard Control: Psychoeducation	119 Healthy and excess weight university students Habitual salty snack food eaters Active Training (MD)= 27 Active Training (SST)= 27 Active Training (MD+SST)= 22 Standard Control= 27	Salty snack food consumption (Ecological Momentary Assessment) Dietary dishinibition (Dishinibition subscale, Eating Inventory)	MD, SST and SST+MD significantly reduced snack consumption. MD and MD+SST (not SST) differed from Psychoeducation on snack consumption. No synergistic effect of MD and SST Moderators: Emotional eating moderated the effect of SST (Greater decrease on snack consumption at lower levels).	NR
Allom & Mullan (2015)	Stop Signal task (SST) Format: computerized Delivery: 10 daily online sessions Active mechanism: Response inhibition	Randomised Between-groups Active Training: Food-specific inhibition (25% of stop signals) Active Control 1: General inhibition (25% of stop signals) Active Control 2: same task, no stop-signals	Study 1 82 university students Active Training= 29 Active Control 1= 25 Active Control 2= 28 BMI (self-reported)= 22.62 (2.64) Study 2 78 university students and staff BMI= 23.11(2.56) Active Training = 27 Active Control 1= 26 Active Control 2= 25	Study 1 BMI (Self-reported) Fat intake (Block food screener) Vulnerability to depletion (Depletion task) Stroop Test Study 2 BMI Fat intake (NCI Percentage Energy from Fat Screener) Vulnerability to depletion (Depletion task) Stroop Test (All measures taken at post-training and one week after)	Study 1 Active training decreased BMI. No evidence that Active Training or Active Control reduce fat intake. Mediators: Changes in vulnerability to depletion. Study 2 No evidence that the Active Training or Active Control reduced fat intake or BMI. Improvements in inhibitory control do not persist at follow up assessment.	Study 1 *BMI* (Change pre to post intervention) Active Control 2 vs Active Training *d*= 0.07 Active Control 1 vs Active Training *d*= 0.07 Study 2 *BMI*(Change pre to post intervention) Active Training vs Active Control 2 *d*= 0.03 Active Training vs Active Control 1 *d*= 0.03

Lawrence et al. (2015b)	Stop Signal task (SST) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Semi-randomly assigned Between-groups Study 1 Active Training: Food and non-food images. Stimulus-specific associations, withold response after signal Active Control: Food and non-food images. Stimulus-specific, double-response after signal	Study 1 54 university students and staff Active Training= 29 Active Control= 25 BMI= 22.9 (3.8)	Study 1, 2 and 3 Taste and calorie intake of crisps and chocolate (Ad-libitum Eating Taste Task) Restrained eating (Dutch Eating Behaviour Questionnaire)	Study 1 Active Training reduced intake of crisps.	Study 1 *Calorie intake** *d*= 0.56
		Study 2 Active Training: Food and non-food images. Stimulus-specific associations, withold response after signal Active Control 1: Food and non-food images, Stimulus-specific, double-response after signal Active Control 2: Instructed to respond as usual ignoring the signal.	Study 2 136 university students and staff Active Training= 44 Active Control 1= 46 Active Control 2= 46 BMI= 23.5 (4.15)		Study 2 No effect on intake. Moderators: marginal effect of training among low levels of dietary restraint.	Study 2 *Intake Signal food ** Active Training vs Active Control 1 *d*= 0.32 *Intake Go food** Active Training vs Active Control 1 *d*= 0.2 Active Training vs Active Control 2 NR
		Study 3 Active Training: Non-food images. Stimulus-specific associations, withold response after signal Active Control 1: Non-food images. Stimulus-specific,double-response after signal Active Control 2: General-stop training (no association between pictures and stop signals)	Study 3 146 female university students and staff Active Training= 47 Active Control 1= 51 Active Control 2= 48 BMI= 22.94 (4.02)		Study 3 Training had no effect on food intake.	Study 3 *Calorie intake*Active Training vs Active Control 1 *d= 0.32* Active Trainingvs Active Control 2 *d= 0.01*

Houben (2011)	Stop Signal task (SST) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Within subject design. 3 conditions (1) Inhibition manipulation: one type of food always paired with a stop signal (2) Impulsive manipulation: one type of food never paired with stop signal (3) Control: third type of food paired with a stop signal on 50% of trials (Types of food: chips, nuts or M&Ms) Inhibitory control (SST) as a contiuous variable	29 female university students BMI= 23.12 (4.27)	Caloric intake, Crisps, nuts and M&Ms (Ad-libitum Eating Taste Task) Inhibitory control (SST)	Participants with low inhibitory control (measured by SST pre training): (1) Consumed more control food and (2) decreased stop food consumption relative to control food. Participants with high inhibitory control: Neither impulsive nor inhibitory manipulation affected food consumption.	NR
Guerrieri et al. (2012)	Stop Signal task (SST) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Randomised Betwen-groups Active Training: Raising proportion of stop trials (up to 50%) Active Control: Raising proportion of go trials up to 100% Standard Control: Instructed to read and summarize two neutral stories.	61 healthy weight female university students Active Training= 20 Active Control= 21 Standard Control= 20 BMI= 22.20 (2.78).	Taste and caloric intake (Ad-libitum Eating Taste Task)	Active Training and Standard Control did not differ on caloric intake. Active Control had significantly higher caloric intake than Active and Standard Control.	*Caloric Intake* NR
Veling et al. (2011)	Go/No-Go task (GNGT) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Study 1 Within-subjects design 2 object type (palatable food vs. control objects) by 2 cue type (go vs. no-go). Chronic dieting as a continuous variable.	Study 1 38 Healthy-weight female university students	Study 1 Response latencies (Go/no-go task)	Study 1 No-go cues inhibited responses toward palatable foods among chronic dieters.	Study 1 No behavioural measure
		Study 2 Randomized Between-groups. Active Training: No-go group (Sweets always paired with a no-go cue) Active Control: Same stimuli, not consistently paired with go/no-go cues.	Study 2 46 University students Chronic dieters BMIActive Training= 21.11 (2.54) Active Control= 21.98 (2.70)	Study 2 Amount of sweets consumed at home after the training.	Study 2 Chronic dieters on the Active Training consumed less sweets.Non dieters'consumption were unafected by training condition.	Study 2 NR

Veling et al. (2013a)	Go/No-Go task (GNGT) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Study 1 Randomised Between-subjects 2 signal conditions (Active vs Active Control) by 2 appetite status (low vs high) Active Training: Foods always paired with no-go cue Active Control: Foods always paired with go cue	Study 1 79 young adults BMI= 22.00 (2.75)	Study 1 and 2 Food choice post training (Computerized task)	Active Training reduced unhealthy food choices and led to higher healthy food choices among the high appetite condition group (Study 1) and when the food was part of their eating habits (Study 2). No effect of active training on low appetite condition.	Study 1 High appetite condition- *Number of choices of healthy food* *d*= 0.9
		Study 2 Randomized Between-subjects 2 signal conditions (stop signal vs control) Frequency of unhealthy food consumption as a contious factor Active Training:Foods always paired with no-go cue. Active Control: Foods always paired with go cue	Study2 44 young adults BMI= 21.61 (2.41)			Study 2 Previous high frequency of unhealthy foods- *Number of choices of healthy food* *d*= 3.29

Adams et al.(2017)	Go/No-Go task (GNGT) and Stop Signal task (SST) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Semi-randomly assigned Between-groups Study 1 Active Training: Food and non-food images, withold response after signal Active Control: Food and non-food images, double-response after signal	Study 1 143 adult participants Restrained eaters Chocolate cravers Active Training= 71 Active Control= 72 BMI not reported	Study 1 Chocolate and Crisps consumption (Ad-libitum Eating Taste Task) Implicit association task (Single-Category Implicit Association Test, SC-IAT)	Study 1 Training condition had no effect on food type consumption.No significant interaction effects on SCIAT.	Study 1 NR
		Study 2 Semi-randomly assigned Between-groups Active Training: (1) SST (food and non-food images, withold response after signal, (2) GNGT no-go (food and non-food images, unhealthy food allways paired with no-go) Active Control: (1) SST (food and non-food images, double-response after signal), (2) GNG go (food and non-food images, no signal trials) Standard Control: Same stimuli, only had to observe	Study 2 197 adult participants Restrained eaters Chocolate cravers Active Training 1= 46 Active Training 2= 35 Active Control 1= 49 Active Control 2= 35 Standard Control= 32 BMI not reported	Study 2 Calorie intake of unhealthy food (Ad-libitum eating taste task)	Study 2 Active GNG training was more effective than Active SST training on reducing unhealthy food consumption. Active training (SST and GNG/no-go) reduced unhealthy food compared to Active control training. Unhealthy food consumption across conditions: Active control 2> Active Training 2= Active Training 1 = Active control 1 = Standard Control.	Study 2 *Unhealthy calorie intake* * Active Training 2 vs Active Control 2 *d*= 1.11 Active Training2 vs Active Control 1 *d*= 0.97 Active Training 2 vs Standard Control *d*= 0.81
Veling et al. (2013b)	Go/No-Go task (GNGT) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Mixed-model design Between subjects factor: Appetite status (low vs high) Within-subjects factor: Signal condition (go vs no-go) and amount of pairings (4 vs 12 vs 24)	50 participants BMI= 22.48 (3.74)	Food choice (Food selection task, computerized) Food evaluation (Attractiveness and tastiness)	Palatable foods associated with no-go cues were less often chosen among high appetite status participants. The amount of pairings had no effect on training. Mediators: Decreased evaluation of palatable foods.	High appetite status *Food Choice* *d*= 1.28
Houben & Jansen (2011)	Go/No-Go task (GNGT) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Randomised Betwen-groups. Active Training: Chocolate pictures paired with no-go cues Active Control 1: Chocolate pictures always paired with go cues Active Control 2: Same pictures not consistently paired with go cues	69 university female students High trait chocolate cravers Active Training= 24 Active control 1= 23 Active control 2= 22 BMI Active Training= 23.46 (3.79) Active Control 1= 21.14 (2.32) Active Control 2= 22.56 (4.05)	Chocolate consumption (Ad-libitum Eating Taste Task) Restraint Scale (RS)	Active Training effectively reduced chocolate consumption compared to Active Control 2 group. No difference between Active Control 1 and Active Control 2 training on chocolate consumption. Higher levels of dietary restraint were associated with decreased chocolate intake.	*Calories consumed* *d*= 0.86

Houben & Jansen (2015)	Go/No-Go task (GNGT) Format: computerized Delivery: Single dose Active mechanism: Response inhibition	Randomised Between-groups Active Training: Chocolate pictures always paired with no-go Active Control: Chocolate pictures always paired with go cues	41 female university students Chocolate consumers Active Training= 21 Active Control= 20 BMI Active Training= 22.58 (3.46) Active Control= 21.77 (2.39)	Chocolate consumption (Ad-libitum eating taste task) Implicit associations (Single-Category Implicit Association Test)	Active Training decreased participants' desire to eat and reduced food intake. Chocolate-go associations significantly reduced afer Active Training.	*Calories consumed* *d*= 0.6
Lawrence et al. (2015a)	Go/No-Go task (GNGT) Format: computerized Delivery: Online four 10-minute sessions Active mechanism: Response inhibition	Randomised Between-groups. Active Training: High energy snack foods always paired with no-go cues Active Control: General response inhibition (Non-food pictures)	83 adult participants High snack consumption Deshinibition over eating Active Training= 41 Active Control= 42 BMI Active Training= 29.28 (5.4) Active Control= 28.5 (4.71)	Weight post treatment Weight 1 month and 6 months follow up assessment (self-reported) Snacking frequency (Food Frequency Questionnaire) during training week, 1 and 6 months after training Energy intake (24-h food diaries) during and after raining Subjetive food ratings (Stimulus evaluation test)	Active Training improved weight loss and decreased daily energy intake and ratings of liking high-energy density foods. Follow-up: Significant reduction in weight on the active group. Both groups reported significantly less snacking at 1 and 6 months.	*Change in weight at post intervention** *d*= 0.57 *Change in energy intake** *d*= 0.5
Kakoschke et al. (2017)	Go/No-Go task (GNGT) and Approach Bias Modification (ABM) Format: computerized/ joystick Delivery: Single dose Active mechanism: Response inhibition / Approach/Avoidance bias	Randomized Between-subjects 2 approach avoidance training conditions (AAT) (active vs control) by 2 control training conditions (GNG) (active vs control) Active Training 1: AAT+GNGT Active Training 2: AAT +GNG Control Active Training 3: AAT Control + GNGT Active Control: AAT Control + GNG Control	240 female university students Tendency to overeat Concerned by weight and diet goals BMI= 22.91 (4.90)	Implicit food evaluation (Recording-free IAT) Caloric intake (Ad-libitum Eating Taste Task) Food choice (Computerized task)	Active Training 1 increased negative implicit evaluations of unhealthy food compared to the other conditions. No effect of training condition on caloric intake. Active AAT predicted first healthy food choice. No additive effect of combined training on food choice.	*Implicit food evaluation* Active Training 1 vs Active Control *d*=0.23 Active Training 1 vs Active Training2 *d*=0.41 Active Training1 vs Active Training 3 *d*=0.40

Vartanian et al. (2016)	Episodic Future Thinking (EFT) Format: Face-to-face Delivery: Single dose Active mechanism: Episodic memory and decision-making	Study 1 Randomised between-groups Active Training: Food EFT (Plan next dinner) Active control (1) Non Food EFT (future non-food activity), (2) Non Food Recall (past non-food activity) and (3) Food recall (Think about their last lunch) Standard Control: Describe an abstract figure. Study 2 Randomized Between-groups Active Training: Physical exercise-based EFT (write about next time they planned to exercise) Active Control: Physical exercise-based recall (write about their past exercise) Standard Control: describe an abstract figure.	Study 1 158 female university students, Unrestrained eaters (Score <15 Restraint Scale) Active Training= 32 Active Control 1= 32 Active Control 2= 32 Active Control 3=31 Standard Control=31 BMI not reported Study 2 74 women Regular exercise activity (2-3 times/week) Active Training=24 Active Control=24 Standard Control=26 BMI: 22.02 (3.53).	Cookie consumption (Ad-libitum Eating Taste Task) Vividness of imagery (Vividness of Visual Imagery Questionnaire; VVIQ) Cookie taste Desire to eat	Study 1 Active Training (food EFT) and Active Control 3 (food-recall) training reduced cookie consumption compared to the other conditions; No significant differences between both trainings. Moderators: no effect of vividness of imagery, liking of cookies or craving on training condition. Study 2 Active Training and Active Control had no impact on participants' cookie consumption.	*Cookie consumption* * Active Training vs Standard Control *d*= 1.58 Active Training vs Active control 1 *d*= 1.08 Active Training vs Active control 2 *d*= 1.35 Active Control 3 vs Standard Control *d*= 1.23 Active Control 3 vs Active Training 1 *d*= 0.79 Active Control 3 vs Active Control 2 *d*= 1.07
Daniel et al. (2013b)	Episodic Future Thinking (EFT) Format: Face-to-face Delivery: Single dose Active mechanism: Episodic memory and decision-making	Randomized Between-groups Active Training: Generate EFT cues during a delay discounting task and ad libitum eating task Active control: Generate cues for general episodic thinking (ET) based on events described in a travel blog, during a delay discounting task and ad libitum eating	26 overweight and obese women Desire to control food intake Active Training= 14 Active Control= 12 BMI= 30.99 (5.80)	Discount of hypothetical monetary rewards (Delay discounting task) Caloric intake (Ad-libitum Eating Taste Task)	Active EFT participants discounted less than Active control ET participants. Active EFT participants consumed fewer calories than did Active Control ET participants.	*Calores consumedd*= 1.09

Dassen et al. (2016)	Episodic Future Thinking (EFT) Format: Face-to-face Delivery: Single dose Active mechanism: Episodic memory and decision-making	Randomized Between-subject Active Training: Food-related EFT cues Active Control: (1) General EFT cues, (2) Food-related episodic recall cues and (3) Non-food related episodic recall thinking	94 University female university students Active Training= 24 Active Control 1= 23 Active Control 2= 23 Active Control 3= 24 BMI= 22.43 (2.75)	Ability to delay gratification (Monetary Choice Questionnaire) Caloric intake (Ad-libitum Eating Taste Task)	Active Training and Active Control 1 (EFT-based) reduced delay discounting. Active Training reduced caloric intake compared to Active Training 2; No difference between non food-related trainings.	Food-related trainings- *Calories consumed* *d*= 0.73
O'Neill et al. (2016)	Episodic Future Thinking (EFT) Format: Face-to-face Delivery: Smartphone delivered, single dose Active mechanism: Episodic memory and decision-making	Randomized Between-subject Active Training: Health-related EFT cues during a food court dinner Active Control: Episodic recall cues related to habitual personal behaviours during a food court dinner.	29 overweight and obese women Active Training= 13 Active Control= 16 BMI not reported	Calorie and macronutrient intake	Active Training reduced calorie intake compared to Active Control training. Active Training participants consumed fewer calories from fat and more protein than did Active Control training participants. No differences on carbohydrate intake.	*Calories consumed* *d*= 1.2 *Percent calories from fat* *d*= 1.32 *Percent calories from protein* *d*= 0.99
Houben et al. (2016)	Working Memory Training (WMT) Format: computerized Delivery: 20-25 online 30-min sessions Active mechanism: Working memory (maintenance and manipulation)	Randomized Between-groups Active Training: visuospatial WM task, backward digit span task and letter span task with progressive difficulty Active control: visuospatial WM task, backward digit span task and letter span task with no progressive difficulty	50 Overweight and obese participants Active Training= 24 Active Control= 26 BMI Active Training= 31.76 (3.79) Active control= 31.38 (3.72)	Caloric intake (Ad-libitum Eating Taste Task) post training Eating disorder psychopathology (Eating Disorder Examination Questionnaire; EDE-Q) Emotional eating (Dutch Eating Behaviour Questionnaire; DEBQ) BMI WM (same tasks as training), (Measures taken post-training and one month after)	Active training reduced psychopathological eating-related thoughts and emotional eating post treatment and at follow-up. Among highly restrained participants, Active training reduced food intake Among participants with strong dietary restraint goals, Active Training reduced eating-related thoughts, overeating in response to negative emotions, and food intake . Active and Active control training improved WM at post-training and follow-up compared to baseline. WM was significantly higher in the Active training condition	*Caloric Intake Post-training* *d*= 0.19 *Caloric Intake Follow-up* *d*= 0.16 *BMI, Post-training* *d*= 0.019 *BMI, Follow-up* *d*= 0

Kemps et al.(2013)	Approach Bias Modification (ABM) Format: Computerized Delivery: Single dose Active mechanism: Approach/Avoidance bias	Randomised Between-subject Active Training: Chocolate-avoidance training (approach of 90% of non-chocolate images and 10% of chocolate images) Active Control: Chocolate-approach training (approach of 90% of chocolate images and 10% of the non-chocolate images)	96 university women Active Training= 48 Active control= 48	Chocolate craving (Visual analougue scale)	Active ABM participants reported less intense cravings, although not significantly. Active Control ABM participants reported signficantly stronger chocolate cravings after the training.	NR
Becker et al. (2015)	Approach Bias Modification (ABM) Format: Computerized/ Joystick Delivery: Single dose Active mechanism: Approach/Avoidance bias	Randomised Between-groups Active Training: Unhealthy food-avoidance training (avoidance of 90% of unhealthy images and 10% of healthy images) Active Control: Avoidance of 50% of unhealthy images and 50% of healthy images	258 female university students Study 1 Active Training= 26 Active Control= 24	Study 1 Implicit food preferences (IAT) Explicit preferences (Participants were asked to choose between a healthy and an unhealthy option after being presented short scenarios) Snack choice	No evidence that the active training improves implicit and explicit food preferences and eating behaviour.	Study 1 *Implicit food preference* NR *Explicit food preference* *d*= 0.52 *Snack Choice* NR
			Study 2 Active Training= 52 Active Control= 52	Study 2 Implicit food preferences (Affective priming task) Explicit preferences		Study 2 *Implicit food preferences* NR *Explicit food preferences* *d*= 0.14
			Study 3 Active Training= 52 Active Control= 51	Study 3 Implicit food preferences (Affective priming task) Food consumption (Ad-Libitum Eating Taste test)		Study 3 Food consumption *d*= 0.46

Schumacher et al. (2016)	Approach Bias Modification (ABM) Format: Computerized/ Joystick Delivery: Single dose Active mechanism: Approach/Avoidance bias	Randomised Between-groups Active Training: Chocolate-avoidance training (approach of 90% of non-chocolate images and 10% of chocolate images) Active Control: Chocolate-approach training (approach of 90% of the chocolate images and 10% of the non-chocolate)	120 healthy-weight and excess weight female university students Active= 60 Active Control= 60 BMI= 23.0 (4.22)	Amount of chocolate muffin consumed (Ad-Libitum Eating Taste test)	No evidence that the active training decreases consumption of chocolate muffin.	*Chocolate muffin consumed d*= 0.37
Dickson et al. (2016)	Approach Bias Modification (ABM) Format: Computerized/ Joystick Delivery: Single dose Active mechanism: Approach/Avoidance bias	Randomised Between-groups Active Training: Chocolate-avoidance training (approach of 90% of non-chocolate images and 10% of chocolate images) Active Control: Chocolate-approach training (approach of 90% of the chocolate images and 10% of the non-chocolate images)	90 university students Active Training= 50 Active Control= 50	Amount of chocolate consumed (Taste test)	No evidence that the active training reduces consumption of chocolate.	*Chocolate consumed d*= 0.31
Smith et al. (2009)	Attentional Bias Modification (AtBM) Format: Computerized Delivery: Single dose Active mechanism: Attentional bias	Randomised Between-groups Active Training: Attend low calorie food words (dot probes replaced low calorie food words in 100% of trials) Active Control: Attend high calorie food words (dot probes replaced high calorie food words in 100% of trials) Standard Control: Attend neutral words (dot probes replaced neutral words in 100% of trials or neutral words in 100% of trials)	56 healthy-weight female university students Active Training= 18 Active Control= 19 Standard Control= 19 BMI Active Training= 20.29 (1.34) Active Control= 20.94 (1.87) Standard Control= 20.92 (1.49)	Food choice (Food selection task)	Active Training intensified dietary restriction.	NR

Kakoschke et al. (2014)	Attentional Bias Modification (AtBM) Format: Computerized Delivery: Single dose Active mechanism: Attentional bias	Randomised Between-groups Active Training: Healthy food cues-attendance training (dot probes replaced healthy food images in 90% of trials) Active Control: Unhealthy food cues-attendance training (dot probes replaced unhealthy food pictures in 90% of trials)	146 university students and mostly healthy-weight	Consumption of healthy snacks (Taste test task)	Active Training was associated with more consumption of healthy than unhealthy snacks.	*Consumption of healthy snacks* *d*= 0.36
Hardman (2013)	Attentional Bias Modification (AtBM) Format: Computerized Delivery: Single dose Active mechanism: Attentional bias	Randomised Between-groups Active Training: Cake-avoidance training (dot probes replaced neutral images in 100% of trials) Active Control: Cake-attendance training (dot probes replaced the cake images in 100% of trials) Standard Control : Neutral images training (dot probes replaced the cake and neutral images in equal frequency)	60 university students Active Training= 20 Active Control= 20 Standard Control= 20 BMI=22.4 (2.7)	Food choice (Food preferences task) Hunger (Visual analougue scale) Food choice (Food preferences task) Hunger (Visual analougue scale)	Active Training was not associated with reductions on hunger or food intake.	*Hunger* NR *Food intake* *d*=0.30

Kemps et al. (2014)	Attentional Bias Modification (AtBM) Format: Computerized Delivery: Single dose Active mechanism: Attentional bias	Randomised Between-groups Study 1 and 2 Active Training: Chocolate-avoidance training (dot probes replaced non-chocolate images in 90% of trials) Active Control: Chocolate-approach training (dot probes replaced chocolate images in 90% of trials)	Study 1 110 female university students and most healthy-weight Active Training= 55 Active Control= 55	Study 1 Chocolate craving (Visual analogue scale) Amount of chocolate and blueberry muffin consumed (Taste test) Attentional bias (Dot Probe Task with neutral stimuli)	Active Training was associated with less chocolate consumption and less intense cravings. Training effects generalised to previously unseen chocolate cues.	Study 1 *Amount of chocolate consumed* *d*= 0.67 *Amount of blueberry muffin consumed* *d*= 0.15 *Chocolate craving* NR
			Study 2 88 female university students and most healthy-weight Active Training= 44 Active Control= 44	Study 2 Chocolate craving (Visual analogue scale) Amount of chocolate and blueberry muffin consumed (Taste test) Attentional bias (Dot Probe Task with chocolate stimuli)		Study 2 *Food craving* *d*= 0.24 *Amount of chocolate consumed* *d*= 0.72 *Amount of blueberry muffin consumed* *d*= 0.46
Bazzaz et al. (2017)	Attentional Bias Modification (AtBM) Format: Computerized Delivery: Four sessions over four weeks Active mechanism: Attentional bias	Randomised Between-groups Active Training: Attend healthy food cues and ignore unhealthy food cues Active Control: Press a computer key to view healthy and unhealthy food images on a computer Standard Control: No intervention	49 Excess weight dieters Active Training= 17 Active Control= 15 Standard Control= 17 BMI Active Training= 32.76 (3.77) Active control= 30.30 (2.98) Standard Control= 33.38 (5.83)	Diet failure rate (number of participants who quit their diet from pre-test to post-test and to the follow-up test) BMI	Active Training was associated with reductions in diet failure rate and BMI.	NR
Kemps et al. (2015)	Attentional Bias Modification (AtBM) Format: Computerized Delivery: 2 conditions (1 and 5 sessions) Active mechanism: Attentional bias	Factorial design Group: Attend (dot probes replaced non-chocolate pictures 90% of trials) and Avoid (dot probes replaced chocolate pictures on 90% of trials) Sessions: Single and multiple trainings	149 female university students and most healthy-weight Attend/Single= 37 Attend/Multiple= 39 Avoid/Single=38 Avoid/Multiple=35	Amount of chocolate consumed (Taste test)	Active Training was associated with less chocolate consumption. These effects were maintained at 24-h and 1-week follow-up only for the participants who received multiple training sessions.	*Chocolate consumption* *d*= 0.54

Veling et al. (2014)	Go/No-Go task (GNGT) and Implementation Intention Format: Computerized Delivery: 4 online sessions in 4 weeks Active mechanism: Response Inhibition/ Attentional bias	Randomised Factorial design Implementation intention condition: dieting versus control Go/no-go task condition: food versus control (neutral images)	113 healthy-weight and excess weight participants and mostly female Food Go/No-Go and Dieting Implementation Intention= 25 Food Go/No-Go and Neutral Implementation Intention= 29 Neutral Go/No-Go and Dieting Implementation Intention= 33 Neutral Go/No-Go and Neutral Implementation Intention= 26	Weight loss	Active implementation intention and inhibitory control trainings facilitated weight loss. Dieting implementation intention facilitated weight loss particularly among people with a strong current dieting goal, whereas the inhibitory control training facilitated weight loss independent of this factor. Instead, inhibitory control training, but not implementation intention, was primarily effective with dieters with a high BMI.	NR
Armitage (2004)	Implementation Intention Format: Homework Delivery: 1 month Active mechanism: Goal management	Randomised Between-groups Active Training: Dieting-Implementation intention Active Control: Implementation intention (lack of volitational strategies)	264 participants Active Training= 138 Standard Control= 126	Dietary intake (Food frequency questionnaire)	Active implementation intention training reduced fat intake, saturated fat intake, and the proportion of energy derived from fat decreased at 1-month follow up.	*Fat intake* *d*= 0.34
Verhoeven et al. (2013)	Implementation Intention Format: Homework Delivery: 3 days Active mechanism: Goal management	Randomised Between-groups Active Training: (1) Single Implementation intentation and (2) Three Implementation intentions Standard Control: Control-Implementation intentation	63 healthy-weight female university students Active Training 1= 21 Active Training2= 21 Standard Control= 21 BMI= 21.33(1.63)	Unhealthy snacking behaviour (Monitoring diary and registaring diary)	Active single-implementation training was effective in decreasing unhealthy snacking, whereas the multiple-implementation training was not.	*Unhealthy snacking* *d*= 0.74

Verhoeven et al. (2014)	Implementation Intention and cue-monitoring Format: Homework Delivery: 7 days Active mechanism: Goal management	Randomised Between-groups Active Training: (1) Implementation intention and snack cue-monitoring training, and (2) Implementation intention and control cue-monitoring training (related to snack consumption frequency and not reasons for snacking), (3) Control implementation intention and snack cue-monitoring training Standard Control: Control implementation intention and control cue-monitoring training	161 healthy-weight and excess weight university studentsBMI= 22.20 (2.64)	Snacking behaviour and caloric intake from unhealthy snacks (Seven-day snack diary)	Cue-monitoring training either or not combined with implementation intentions reduced unhealthy snacking behaviour compared to control.	*Calorie intake* Active 1 vs Control *d*= 0.29 *Snacking Frequency* Active 1 vs Control *d*= 0.44
Benyamini et al. (2013)	Implementation Intention Format: face-to-face Delivery: 10 weeks Active mechanism: Goal management	Non-randomised Between-groups Active Training: Standard diet and (1) behavioural intention (participants rated the frequency of planned use of a list of weight control techniques) or (2) implementation intention training (participants rated planned use of the techniques and also chose 2 techniques and formulated a plan of how to carry then) Standard Control: Standard diet only	632 excess weight participants Active Training 1= 203 Active Training 2= 239 Standard Control= 190	Body mass index	Active implementation intention and behavioural intention trainings were associated with 40% more weight loss than the control condition. No differences were found between conditions at 3 and 12 months after the intervention.	NR

van Koningsbruggen et al. (2014)	Implementation intention and Go/No-Go task (GNGT) Format: computerized/ face-to-face Delivery: Single dose (GNGT) and 1 week (implementation intention) Active mechanism: Response inhibition/ Goal management	Randomised Between-groups Active Training: (1) Go/No-Go (images of sweets were always accompanied by a no-go cue, and neutral images with either no-go or go cues), (2) Implementation Intention and, (3) Go/No-Go and Implementation intention Standard Control: Go/No-Go (images of sweets were accompanied by either a no-go or a go cue) and implementation intention (goal intention only)	Study 1 91 healthy-weight university students Active Training 1= 24 Active Training 2= 20 Active Training 3= 23 Standard Control= 24 BMI (self-reported)= 22.08 (2.87) Study 2 88 healthy-weight university students Active Training 1= 24 Active Training 2= 20 Active Training 3= 23 Standard Control= 22 BMI= 21.63(2.32)	Study 1 Amount of sweets selected (Sweet shop environment) Study 2 Amount of sweets selected (Snack dispenser task)	Both active trainings (Go/No-Go and implementation intention) reduced the amount of sweets selected in the sweet shop environment and the snack dispenser. Combining the interventions did not lead to additive effects.	NR
Tam et al. (2010)	Implementation intention Format: homework Delivery: 2 days Active mechanism: Goal management	Randomised Between groups Active Training: (1) Promotion-focused implementation intentions (participants picked 3 healthy snacks and formed implementation intentions to eat more of these 3 snacks) and (2) Prevention-focused implementation intentions (participants picked 3 unhealthy snacks and formed implementation intentions to avoid eating them) Standard Control: No implementation intentions	559 healthy-weight and excess weight university students Active Training 1= 221 Active Training 2= 209 Standard Control= 129 BMI (self-reported)= 23.8 (4.01)	Healthy and unhealthy snacks consumed over a 2-day period (Self-reported online food diary)	Participants with weak unhealthy snacking habits consumed more healthy snacks when forming any type of implementation intentions (regardless of match or mismatch with their regulatory orientation), while participants with strong unhealthy snacking habits consumed more healthy snacks only when forming implementation intentions that matched their regulatory orientations.	NR

* Effect size calculation reported by authors
NR= not reported

Table 2. Summary of the effect of cognitive trainings on main outcomes among healthy weight and excess weight participants.

Note. +F: Positive findings; –F: Negative findings; N/A: Not Available. Superscript numbers indicate references, as following: *Response Inhibition*: (1) Houben, 2011; (2)

	Trainings	**Response Inhibition**		**Episodic Future Thinking**		**Working Memory**		**Approach Bias Modification**		**Attentional Bias Modification**		**Implementation Intentions**	
Outcomes		Healthy Weight	Excess Weight	Healthy Weight	Excess Weight	Healthy Weight	Excess Weight	Healthy Weight	Excess Weight	Healthy Weight	Excess Weight	Healthy Weight	Excess Weight
Laboratory measures	*Food Intake*	+F (1-3) -F (4-7)	+F (1,2) -F (6*)	+F (15,16)	+F (17)	N/A	N/A	-F (6*,20,21)	- F (21)	+F (24)	N/A	N/A	N/A
	Food Choice/ Craving	+F (8,9,10*)	N/A	N/A	N/A	N/A	N/A	+ F (6*) -F (22,23)	N/A	+F (24,26,27) -F (25)	N/A	N/A	+F (10*)
Clinical outcomes	*Diet*	+F (11*) -F (12)	+F (11*,14)	N/A	+F (18)	N/A	+F (19)	N/A	N/A	+F (28)	N/A	+F (30*-33)	+F (33)
	Weight	+F (13*) -F (12)	+F (13*,14)	N/A	N/A	N/A	-F (19)	N/A	N/A	N/A	+F (29)	+F (13*,34)	+F (13*,34)

Houben & Jansen, 2011; (3) Houben & Jansen, 2015; (4) Adams et al. 2017; (5) Guerrieri et al. 2012; (6) Kakoschke et al. 2017; (7) Lawrence et al. 2015b; (8) Veling et al. 2013a; (9) Veling et al. 2013b; (10) van Koningsbruggen et al. 2014; (11) Forman et al. 2016; (12) Allom & Mullan, 2015; (13) Veling et al. 2014; (14) Lawrence et al. 2015a; *Episodic Future Thinking:* (15) Dassen et al. 2016; (16) Vartanian et al. 2016; (17) Daniel et al. 2013b; (18) O'Neill et al. 2016; *Working Memory:* (19) Houben et al. 2016; *Approach Bias Modification:* (6) Kakoschke et al. 2017 ; (20) Dickson et al. 2016; (21) Schumacher et al. 2016; (22) Kemps et al. 2013; (23) Becker et al. 2015; *Attentional Bias Modification:* (24) Kemps et al. 2014; (25) Hardman, 2013; (26) Kakoschke et al. 2014; (27) Smith et al. 2009; (28) Kemps et al. 2015; (29) Bazzaz et al. 2017; *Implementation of Intentions:* (13) Veling et al. 2014; (30) Verhoeven et al. 2013; (31) Verhoeven et al. 2014; (32) Armitage, 2004; (33) Tam et al. 2010; (34) Benyamini et al. 2013. *Studies using combined interventions: (6) *Response inhibition + Approach Bias Modification*; (10) & (13) *Response Inhibition + Implementation Intentions*; (11) *Response inhibition + Mindful decision making*; (30) *Implementation Intentions + cue monitoring.*

Table 3. Neuromodulation studies aiming to modify eating behaviors.

Authors	Technique and Stimulation Protocol	Design	Participants	Main outcomes	Main Findings	Effect size (Cohen's *d*)
Jauch-Chara et al. (2014)	tDCS *Target:* DLPFC Active: anode right (5 cm anterior to the motor cortex target of the left first interdigital muscle) / cathode left forehead) Control: Same position, no current flow Parameters: 8 daily sessions, 1mA, 20 min, 35 cm² sponge electrodes Active mechanism: Activation of the dorsolateral prefrontal cortex	Randomized, single-blind Crossover experiment Counterbalanced	14 healthy young male Low cognitive restraint and disinhibition, normal susceptibility to hunger (Three-Factor Eating Questionnaire) BMI 20 to 25 (22.65+- 0.34)	Caloric intake (Ad-libitum eating taste task: standardized test buffet) Bodyweight Appetite measures (Hungry and specificity for sweet and savory via VAS)	Caloric intake reduced by 14% after 8-d of Active tDCS compared to Control stimulation. Significant reduction on caloric intake from pre to post intervention after Active tDCS but not after Control stimulation No effect of stimulation on body weight Active tDCS reduced self-reported appetite scores	NR
Fregni et al. (2008)	tDCS *Target*: DLPFC Active: (1) anode left (F3)/cathode right tDCS, (2) anode right (F4)/cathode left tDCS Control: Same position, sham stimulation *Parameters:* 3 sessions, max output of 10 mA, electrodes of 35 cm2, 48 h intersession interval. Active mechanism: Activation of the dorsolateral prefrontal cortex	Randomized, double-blind Cross-over experiment	21 Healthy females Cravings> 3 times/day and strong urges to eat foods used on the experiment BMI not reported	Craving (Urge to eat, VAS) Caloric intake (Ad-libitum eating taste task)	Craving was reduced by Active 2 but not Active 1 stimulation and increased after Standard Control. Caloric intake was lower after both Active Stimulation conditions compared to Standard Control.	NR
Gluck et al. (2015)	Study 1 tDCS *Target:* DLPFC Active: cathode left (F3)/ anode left forearm Control: Same position, sham stimulation Study 2 Target: LDLPFC Active: anode left (F3)/cathode above the right eye Control: Same position, sham stimulation *Parameters* for both: 3 -40 min sessions (1/day), 2 mA; two 5 x 5 cm sponge electrodes Active mechanism: Activation of the dorsolateral prefrontal cortex	Study 1 Randomized, double-blind, sham-controlled parallel study Study 2 Previous study 1 participants	Study 1: - (not useful data) Study 2: 9 Obese females	Caloric intake (Ad-libitum eating taste task) Weight (during 3-day ad-libitum intake period and post-intervention)	% weight change was lower in the cathodal condition (St1) compared to the anodal condition (St2) during both the 3-day ad-libitum intake and overall inpatient periods. Study 2 Fewer calorie intake from fat and soda after Active vs Control tDCS No differences in body weight nor % weight change	Study 1 - Study 2 *Fat (g/day)* *d= -0.37* *Soda (kcal/day)* *d= -0.24*

Kekic et al. (2014)	tDCS *Target:* DLPFC Active: anode right (F4), cathode left F3 Control: Sham stimulation, same position. Parameters: Single 20 min session, 2mA; two 25 cm2 surface sponge Active mechanism: Activation of the dorsolateral prefrontal cortex	Randomized, double-blind Within-subjects crossover design	17 Healthy women Food cravings>1 day BMI= 23.81 (2.60) BMI Range: 19.90–29.30	Caloric intake (3 min Ad-libitum eating taste task) Discount of hypothetical monetary rewards (Temporal discounting task) Food cravings Food Challenge Task (FCT) Food craving (Food Craving Questionnaire-State) Hormonal stress response (saliva sample)	No difference on food consumption or Temporal discounting. Craving for sweet but not savory food reduced after Active stimulation. Participants that made more reflective choices were more susceptible to tDCS effects.	NR
Lapenta et al. (2014)	tDCS *Target:* DLPFC Active: anode right F4/cathode left F5 Control: Same position, sham stimulation *Parameters:* 2 mA, 1-20 min session, 35 cm2 rubber electrodes, 1 week interval between conditions Active mechanism: Activation of the dorsolateral prefrontal cortex	Within subjects Crossover design	9 Healthy females Craving> 3 times/day Strong urges to eat foods on experiment. BMI= 21.9 (1.63)	Food craving (VAS) Caloric intake (Ad-libitum eating taste task) EEG recording post tDCS Go/No-go task during	Reduced craving after active tDCS. Significantly less calorie intake after active vs sham training. Non-significant reduction on N2 mean amplitude negativity and significant increase on P3 amplitude after active tDCS.	*Caloric intake* *d*=1.03
Goldman et al. (2011)	tDCS *Target:* DLPFC Active: anode right (F4), cathode left (F3) Control: Same position, sham stimulation P*arameters:* Single 20 min session, 2.0 mA , sponge electrodes (size not reported) Active mechanism: Activation of the dorsolateral prefrontal cortex	Within subjects, double-blind Crossover study	19 Healthy subjects BMI= 27.25 (6.2)	Food craving (computerized VAS) Caloric intake (Ad-libitum eating taste task)	Inability to resist food reduced by 27% after Active stimulation compared to 11% on Control condition. Active tDCS decreased craving for sweet and carbohydrates (no difference on high fat food or fast-food images) No difference on caloric intake.	NR
Montenegro et al. (2012)	tDCS *Target:* Left DLPFC Active: anode F3, cathode over supraorbital contralateral area (Fp2) Control: Same position, sham stimulation *Parameters*: 1) tDCS: Single session, 20 min, max 10mA , 35 cm2 sponge electrodes; 2) Physical activity: isocaloric exercise bouts. 48–120 hours interval between conditions Active mechanism: Activation of the dorsolateral prefrontal cortex	Randomized Within subjects Crossover study	9 excess weight subjects (5 men/4 women) BMI= 28.2 BMI range= 25.2–43.5	Appetite sensation (VAS, (1) pre; (2) Post-tDCS; (3) post-exercise, (4) 30 min post-exercise)	Active tDCS significantly decreased the desire to eat. Active tDCS plus exercise had increased suppressing effect on desire to eat compared to Active tDCS or physical exercise isolated effects. Appetite sensation after exercise recovery was lower after Active tDCS compared to Control.	NR
Ljubisavljevic et al.	tDCS *Target:* Right DLPFC	Randomized Double blind	27 Healthy subjects (19 men/ 8 women)	Food craving (Food Craving Questionnaire-State and Trait;	A single session of tDCS significantly decreased the intensity of current food craving (Active and Control	*Current Food craving* *(After 1 session)*

(2016)	Active: anode F4, cathode left forehead. Control: Same position, sham stimulation *Parameters*: 1) Active: 5 daily sessions, 20 min, 2mA; 2) Control: First day 20 min session, 2mA, days 2-5: sham stimulation. Both: 35 cm² sponge electrodes Active mechanism: Activation of the dorsolateral prefrontal cortex		Food Cravers BMI= 25.6 (4.4)	Food Craving Inventory)	trainings) but had no effect one month after training (Control condition). Active training (5 consecutive sessions) significantly reduced 1) habitual food craving compared to baseline and 2) current and habitual craving 1-month after training.	*d=0.51* *Habitual Food craving (Change Pre post Training, Active)* *d=0.44* *Habitual Food craving (Post 1 month)* *d=0.68* *Current Food craving (Post 1 month)* *d= 1.6*
Uher et al. (2005)	TMS *Target:* Left DLPFC Active: 5 cm anterior to the site of maximal abductor pollicis brevis stimulation, same parasagittal plane Control: Same position, sham stimulation *Parameters:* single session, 20 trains of 5 sec/55 sec inter train. Freq 10 Hz 110% intensity. Total 1000 pulses over 20 min. Active mechanism: Activation of the dorsolateral prefrontal cortex	Randomized Double blind Parallel group	28 Healthy women Strong/very strong urge to eat the experimental foods cravings>3/week Active= 13 Control= 15 BMI Active= 24.7 (5.5) BMI Control= 23.3 (5.3)	Craving (Urge to eat, VAS) Caloric intake (Ad-libitum eating taste task)	Food craving remained stable after Active TMS and increased after Control condition. No differences in ad libitum eating between groups.	*Caloric intake* *d*= 0.27
Barth et al. (2011)	TMS *Target:* Left PFC Active: 5 cm anterior to motor cortex target (M1) along a parasagittal line Control: Same position, sham stimulation (matched with respect to perceived painfulness stimulation) *Parameters:* 10 Hz, at 100% rMT, 10s-on and 20 s-off for 15 min, total 3000 pulses in single session. Active mechanism: Activation of the dorsolateral prefrontal cortex	Within-subjects Cross-over design	10 Healthy women cravings>3/week BMI= 27.8 (8)	Food craving (Computerized VAS)	Significant less food craving after both Active and Control TMS, but no difference between conditions.	NR

Harat et al. (2016)	DBS *Target:* bilateral nucleus accumbens stimulation *Parameters*: (-) polarity to contact one electrode and (+) on the contact 4 electrodes, 208 ms pulse width, frequency 130 Hz, initially 2 mA stimulation progressively up to 3.75 mA) Active mechanism: Modulation of the nucleus accumbens	Case report	19 years old female with hypothalamic obesity BMI= 52, 9	1, 3, 7 and 14 months after surgery Bodyweight (BMI) Neuropsychological test battery (WCST, TMT, Stroop Color-Word Interference Test)	Decrease on bodyweight (from 151.4 to 138 kg after 14 months). Neuropsychological test results were intact.	-
Whiting et al. (2013)	DBS *Target:* Lateral hypothalamic area (LHA) *Parameters*: monopolar stimulation (contact cathode, pulse generator anode), 3 different contacts (Contact 0 most distal, Contact 3 most proximal; each tested in a different day), 90 m sec pulse width, frequency 185 Hz kept constant. Voltage increased by 1 V every hour up to 7 V. Active mechanism: Modulation of the lateral hypothalamic area.	Pilot study (3 case reports)	3 Case series Failed bariatric surgery Subj 1: Female, 60 y, BMI: 49.4 Subj 2: Female, 50 y, BMI: 48.1 Subj 3: Female, 45 y, BMI: 45	Safety measures Resting metabolic rates (measured by a respiratory chamber) Weight loss at follow up (range 30-39 months)	Weight loss trends after monopolar DBS stimulation via specific contacts-settings. Increased resting metabolic rate.	-
Ihssen et al. (2016)	Motivationa lNeurofeedback *Target*: Based on the statistical contrast between palatable foods and neutral pictures, a target area showing reliable activation in the statistical maps derived from the localizer run was selected for each participant. Target areas comprised clusters in the amygdala in 5 participants, the putamen/caudate in 2 participants, and the insula, thalamus and parahippocampal gyrus in one participant, respectively. *Parameters*: Participants were instructed to down regulate activation area. Active mechanism: Inhibition of the 'motivational networks'	Pilot study Single Session	10 healthy females BMI= 23.53	Hunger, Satiety and Craving (5-point scale questionnaire)	Significant reduction of hunger after Neurofeedback and an association between down-regulation success and the degree of hunger reduction.	*Hunger* * *d*= 0.92

Schmidt and Martin (2015)	Cue-exposure Neurofeedback Parameters: Participants were instructed to develop a strategy to reduce EEG high beta activity according to the feedback presented on screen. Active mechanism: Inhibition of EEG high beta activity after food cue exposure	Randomized Pilot Study 10 sessions Active: Cue-Exposure Neurofeedback group Control: Waiting List Control Group	Healthy-weight and excess weight participants Active= 14 Control= 13 BMI Active= 37.93 (11.18) BMI Control= 31.15 (9.56)	Number of weekly overeating episodes (5-point scale questionnaire) and food craving (Food Craving Questionnaire) at post-treatment and 3-month follow-up	Post-treatment and 3-month follow-up: The number of weekly overeating episodes was significantly reduced in the active training compared to control. 3-month follow up: Additional benefit effects on food craving	*Overeating* (episodes/week) *d*= 0.99

NR= Not reported

Table 4. Summary of the effect of neuromodulation interventions on main outcomes among healthy weight and excess weight participants.

	Trainings	**Transcraneal Direct Current Stimulation**		**Transcraneal Magnetic Stimulation**		**Deep Brain Stimulation**		**Neurofeedback**	
Outcomes		Healthy Weight	Excess Weight	Healthy Weight	Excess Weight	Healthy Weight	Excess Weight	Healthy Weight	Excess Weight
Laboratory measures	*Food Intake*	+F (1, 2) -F (3, 4)	-F (3, 4)	-F (9)	-F (9)	N/A	N/A	N/A	N/A
	Food Choice/ Craving	+F (1-4)	+F (3, 4, 7)	+F (9) -F (10)	+F (9) -F (10)	N/A	N/A	+F (13)	+F (13)
Clinical outcomes	*Craving/ Diet*	+ F (5, 6)	+F (5, 8)	N/A	N/A	N/A	N/A	+F (14)	+F (14)
	Weight	- F (6)	- F (8)	N/A	N/A	N/A	+F (11, 12)	N/A	N/A

Note. +F: Positive findings; –F: Negative findings; N/A: Not Available; Superscript numbers indicate references, as following: *Transcraneal Direct Current Stimulation:* (1) Fregni et al. 2008; (2) Lapenta et al. (2014); (3) Goldman et al. (2011); (4) Kekic et al. 2014; (5) Ljubisavljevic et al. 2016; (6) Jauch-Chara et al. (2014); (7) Montenegro et al. 2012; (8) Gluck et al. 2015; *Transcraneal Magnetic Stimulation:* (9) Uher et al. 2005; (10) Barth et al. 2011; *Deep Brain Stimulation*: (11) Harat et al. 2016; (12) Whiting et al. 2013; *Neurofeedback*: (13) Ihssen et al. 2016; (14) Schmidt and Martin 2015.