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Executive function in weight loss and weight loss maintenance: a conceptual review and novel neuropsychological model of weight control

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Abstract Weight loss maintenance is a complex, multifaceted process that presents a significant challenge for most individuals who lose weight. A growing body of literature indicates a strong relationship between cognitive dysfunction and excessive body weight, and suggests that a subset of high-order cognitive processes known as executive functions (EF) likely play an important role in weight management. Recent reviews cover neuropsychological correlates of weight status yet fail to address the role of executive function in the central dilemma of successful weight loss maintenance. In this paper, we provide an overview of the existing literature examining executive functions as they relate to weight status and initial weight loss. Further, we propose a novel conceptual model of the relationships between EF, initial weight loss, and weight loss maintenance, mapping specific executive functions onto strategies known to be associated with both phases of the weight control process. Implications for the development of more efficacious weight loss maintenance interventions are discussed.

Keywords Obesity · Review · Weight loss maintenance · Executive function · Behavioral intervention · Conceptual maintenance model

Obesity is one of the predominant healthcare concerns in the United States (Finkelstein et al., 2010; Fryar et al., 2015; Ogden et al., 2012) with recent reports suggesting that 38% of adults and 17% of youth are living with obesity (Ogden et al., 2014, 2016; Flegal et al., 2016). Compared to normal or healthy weight individuals, those with obesity are at higher risk for many serious health conditions including all causes of morbidity and mortality, heart disease, stroke, type 2 diabetes, certain types of cancer, and dementia (Fryar et al., 2015). The economic, medical, and social costs of excessive weight are well documented and predicted to increase by $48–66 billion per year by 2030 (Finkelstein et al., 2012; Wang et al., 2011). Reflecting these significant health and economic concerns, the United States' Surgeon General has identified the obesity crisis among his top priorities.

Modest weight loss (5–10% of body weight) can be reliably achieved through several evidence-based methods and is associated with significant health benefits (MacLean et al., 2015; Wing & Hill, 2001). Maintaining weight loss, however, has proven to be a more elusive accomplishment; most weight is regained within 3–5 years (MacLean et al., 2015; Wadden & Stunkard, 1986; Wadden et al., 1988). As noted by a recent workgroup of weight management experts convened by the National Institutes of Health, the challenge of weight loss maintenance (WLM) is one of the field's most significant dilemmas (MacLean et al., 2015). Data from several sources suggests that the processes that drive and support initial weight loss are theoretically and empirically distinct from those associated with weight loss maintenance (Williams et al. 1996; Rothman, 2000; Elfhag & Rössner, 2005). In a large, cross-sectional survey of 1165 U.S. adults, only 8 of 36 weight-control strategies (22%) were found to be associated with both weight loss and WLM, while 4 were associated uniquely with maintenance. Notably, poor agreement (kappa = 0.22) was reported between practices uniquely associated with weight

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loss and WLM, indicating each process likely requires a distinct set of skills and behaviors (Sciamanna et al., 2011).

Attempts to understand the process of successful weight-related behavior change have traditionally focused on behavioral or social-cognitive predictors of success (McGuire et al., 1999; Wadden et al., 2009; Wing et al., 1998; Wing et al., 2006). More recently, advances in neuroscience and neuropsychology have fueled increased interest in neurocognitive processes underlying obesity and weight management. The field is still nascent – relatively few studies have explored neurocognitive correlates of weight loss, and even fewer have examined neurocognitive correlates of long-term maintenance. This is an area ripe for investigation as work in other health-related domains (e.g., physical activity, smoking cessation, and stress regulation) suggest neuropsychological variables are intricately involved in health-behavior change and health-maintaining behavior (Hall et al., 2006, 2008; Loprinzi et al., 2015; Williams et al., 2009; Williams & Thayer, 2009). Given the complex and multifaceted nature of weight loss and WLM, a specific subset of processes known as executive functions, involved in high-order or top-down functioning, are likely among the most highly implicated cognitive systems in successful weight management. The pivotal role that executive function might play in long-term weight loss success requires attention in conceptual models of weight management that can guide future research, and ultimately, integrate executive function training strategies into our existing framework of behavioral weight loss intervention.

Executive function, obesity, and weight management

Defining and measuring core constructs

Debate exists regarding which functions comprise the core elements of executive function. However, several key executive skills are consistently cited in research and clinical domains of neuropsychology including inhibition, working memory, planning, organization, and task-switching (Alvarez & Emory, 2006; Miyake et al., 2000; Suchy, 2009).

In an influential paper exploring the unity and diversity of executive function, Miyake et al. (2000) examined the extent to which functions attributed to executive ability reflect a single underlying "executive system" or truly distinct subcomponents. Three central components of executive function emerged as central to the model: shifting between tasks or mental sets (i.e. "shifting"), updating and monitoring of working memory (i.e. "updating"), and inhibition. Results indicate that these components of executive function are clearly distinguishable, however moderate correlations also exist between the three factors, representing shared underlying cognitive mechanisms (Miyake et al., 2000). Regardless of how executive functions are defined, the distinction between general cognitive function and executive function is important to note. Executive functions are defined as a subset of general cognitive function, involved specifically in high-order, self-regulatory, and volitional processes (Baumeister & Vohs, 2003). Additionally, executive functions are typically described in terms of "how" behavior is expressed, while general cognitive function is discussed in terms of "what" behavior or "how much" a behavior is exhibited (Lezak et al., 2012).

Weight-related health behavior change and WLM are sufficiently complex processes to necessitate the recruitment of executive skills. Understanding these complex processes from an integrated perspective requires mapping executive functions (rather than general cognitive functions alone) onto known behavioral correlates of successful weight management. While executive functions are commonly measured using computer and task-based assessment measures (e.g., Stroop color-word task, Go-No-Go, Trail-Making, Wisconsin Card Sort Task, Tower of London, and Iowa Gambling Task) or administered concordantly with scanning methods such as fMRI or EEG,[1] it is often difficult to conceptualize how outcome variables provided by standardized cognitive test batteries might translate into behavioral outputs. Intervention design and implementation focused on training and strengthening executive performance depends, fundamentally, on a clearer understanding of how task-based assessment measures of executive performance translate into real world behaviors. To fully understand the complex relationship between executive function and weight maintenance, and how executive functions might contribute to improved long-term health change, it is crucial to link high-order cognitive performance to specific weight-related behavioral constructs. Furthermore, elucidating cognitive moderators of successful maintenance will allow clinicians and researchers to determine who is at highest risk for regain following initial weight loss, and to develop novel treatment strategies to support these individuals in long-term maintenance. In developing this model, we will review the extant literature that has primarily focused on executive

[1] The scope of this paper does not allow for an adequate review of fMRI and EEG findings regarding executive function and weight loss maintenance. It should be noted that executive and prefrontal functions do not operate in isolation. Neuroimaging data serve to highlight the vastly complex and integrated nature of correspondence between PFC and many other neural networks implicated in eating behavior and weight management broadly (Jansen et al., 2013, Murdaugh et al., 2012; Szabo-Reed et al., 2015).

function ability in adults with obesity, as well as the potential bidirectional association between weight loss and executive function. Far fewer studies have explored potential implications of executive function beyond the initial weight loss phase.

Executive functioning in overweight and obesity

Evidence suggests that obesity is a risk factor for the development of neurocognitive deficits, including poor performance on tests of general cognitive functioning and executive functioning (Cserjesi et al., 2009; Fitzpatrick et al., 2013; Gunstad et al., 2007; Prickett et al., 2015). Cross-sectional designs indicate that executive impairments most consistently found in adults with obesity, compared to normal weight controls, include inhibition, decision-making, concept formation, and set shifting. These deficits are observed independent of age, general cognitive ability, education, and health factors including diabetes and hypertension (Boeka & Lokken, 2008; Brogan et al., 2011; Cserjesi et al., 2009; Davis et al., 2004; Fagundo et al., 2012; Fergenbaum et al., 2009; Gunstad et al., 2007; Smith et al., 2011; Roberts et al., 2007), although there is some evidence to suggest that the obesity-executive function link may be more pronounced in adults with more complicated obesity profiles (e.g., metabolic syndrome, experiences of loss of control eating) (Fergenbaum et al., 2009). For example, in those who experience loss of control (LOC) eating, it is hypothesized that deficits in executive function (including cognitive inflexibility, poor self-regulation, planning deficits, and difficulty with inhibition and delayed reward) likely lead to loss of control or binge eating episodes; significant risk factors for the development of obesity (Manasse et al., 2014; Manasse et al., 2015a, b). Cross-sectional analyses indicate adults with obesity meeting criteria for LOC eating, regardless of frequency or size of episode, show significantly greater executive deficits, specifically in self-regulatory control and planning, than non-LOC participants with obesity (Manasse et al., 2014). More recently, the same group reported select deficits in executive function among overweight women diagnosed with binge eating disorder (BED), compared to overweight women without BED. Differences emerged in the areas of problem solving, inhibition, and delayed gratification, but not in set shifting, working memory, or risk taking (Manasse et al., 2015a).

While most studies in this area are cross-sectional in nature, longitudinal associations (follow-up ranging from 5 to 27 years) between midlife obesity and risk for poor neurocognitive and executive outcomes have been reported (Cournot et al., 2006; Fitzpatrick et al., 2009; Gunstad et al., 2010; Gustafson, 2008; Kivipelto et al., 2005; Whitmer et al., 2005, 2008). Specifically, Cournot et al. (2006) report higher baseline BMI is associated with cognitive decline over 5 years. Additionally, findings from Gunstad et al. (2010) suggest that higher body composition at baseline is associated with more rapid decline in general cognitive and executive function. Notably, longitudinal outcomes also indicate that midlife obesity may be a risk factor for the development of dementia and Alzheimer's disease, adjusting for demographics and cardiovascular risk factors (Gustafson, 2008; Fitzpatrick et al., 2009; Kivipelto et al., 2005; Whitmer et al., 2005, 2008). Together these results suggest that adults with obesity may not only be prone to experience a range of executive function impairments, but may also be at increased risk for neurocognitive deficits later in life. The temporal direction of these relationships remains controversial however, executive function deficits appear to map onto several potential behavioral risk factors for the development of excessive weight, including difficulty planning regular eating patterns, inability to delay gratification or inhibit prepotent responses to highly palatable foods, and difficulty updating goal-relevant information related to weight loss. Additional research is needed to fully elucidate underlying neurophysiological and neurocognitive mechanisms leading to increased risk for obeseogenic behavior and long-term neurocognitive consequences. An important next step is to examine the impact that executive function in adulthood may have on weight loss outcomes.

Impact of executive functioning on weight loss

Self-regulation, comprised of planning ability, inhibitory control, initiation, and updating goal-directed behavior, is a significant predictor of successful health behavior change. Given the obvious overlap between behaviors defined as "self-regulatory" and those defined as executive functions, it is reasonable to hypothesize that individual differences in executive function might also predict individual differences in health-behavior outcomes, including weight maintenance success. In fact, compelling evidence from childhood and adolescent health research suggests that executive function, measured in early childhood, is correlated with eating behavior in cross-sectional analyses (Pieper & Laugero, 2013), and predictive of a range of health outcomes later in life, including body mass index (BMI) and physical activity (Guxens et al., 2009; Marteau & Hall, 2013; Moffitt et al., 2011). Preschool children with higher cognitive function scores had a lower likelihood of being overweight at 2-year follow-up (Guxens et al., 2009). Poor cognitive control, measured in children age 3 to 11, was associated with greater health concerns (including metabolic and weight-related problems) at 32-year follow-up (Moffitt et al., 2011). Adjusting for demographics, IQ, and education level, executive functions have also been shown to be associated with non-weight specific health behaviors including smoking, alcohol use, and sleep hygiene in adults using cross-sectional (Hall et al., 2006), and prospective designs (Booker & Mullan, 2013; Moffitt et al., 2011). Although these studies did not examine the impact of executive function performance on weight loss or WLM specifically, the findings are noteworthy as they suggest a unique contribution of executive function on general health behavior beyond that of IQ, socioeconomic status, or educational attainment.

Converging findings suggest that various executive functions may act as moderators in the relationship between eating intention and eating behavior (Hall et al., 2008; Kuijer et al., 2008; Nederkoorn et al., 2010). Hall et al. (2008) report that executive control moderates the effect of intention to make healthy dietary choices and actual eating behavior at 1-week follow-up, such that individuals with strong intention made significantly fewer healthy food choices if they had poor executive function, compared to participants with weak intention and strong executive skills. Individuals with implicit biases for snack foods and poor eating restraint were also more likely to exhibit poor decision-making and weight gain at 1-year follow-up if they had low executive control (Nederkoorn et al., 2010). It is also reported that inhibition is a stronger predictor of healthy dietary choice for those exhibiting better executive function skills (Hall et al., 2008), suggesting that the intention-behavior relationship is not uniform, but likely moderated by specific executive functions and individual executive ability. Recently, the same group reported that, in follow-up analyses, executive function was the only significant predictor of high fat intake, as well as fruit and vegetable consumption at 1 year, when included in a model with conscientiousness and many other personality characteristics (Hall & Fong, 2013). These results demonstrate that executive function may be a more powerful explanatory variable for weight-related health behaviors than other characteristics typically studied.

Distinct components of executive function also appear to be predictive of distinct weight-related behaviors. Longitudinal designs have demonstrated that engagement in healthy choices, such as increased physical activity and consumption of fruits and vegetables, utilizes a unique set of executive functions, including executive control, updating, and initiating, while avoidance of health-risk behaviors (e.g. consumption of high fat foods, snacking, and disinhibited eating), utilizes a separate set of executive functions, including task-switching, inhibitory control, and flexibility (Allan et al., 2011; Allom & Mullan, 2014; Hall et al., 2006). Similar associations were reported among young adults in a cross-sectional analysis using self-report measures of executive function (Limbers & Young, 2015). Each of these behaviors are crucial to the initial weight loss phase (Rothman, 2000; Wing & Hill, 2001), however, successful weight loss maintenance introduces significant challenges unique from initial weight loss.

These results highlight several important points. First, specific executive functions may be associated with the initiation and inhibition of health behaviors known to directly impact weight outcomes. Second, executive functions that predict healthy eating patterns appear to be distinct from those that predict unhealthy eating. Findings suggest that initiation of healthy behaviors has separate executive function determinants from unhealthy behaviors that must be avoided or inhibited to lose or maintain weight loss. These distinctions will allow researchers to map executive functions onto specific weight-related outcomes, and to generate more informed hypotheses regarding executive function-WLM relationships. From a clinical perspective, longitudinal studies implementing standardized executive function batteries are necessary to more thoroughly examine the impact of executive function on long-term maintenance success. Results of such studies will serve to inform the design and implementation of executive-focused modules into existing behavioral weight loss programs, with the goal of targeting maintenance-related health behaviors that require the greatest executive resources.

Finally, literature indicates that change in executive function may be an important, and more consistent, predictor of weight-related behavior and weight change than executive function measured at a single time point (Best et al., 2014; Bryant et al., 2012; Dalle Grave et al., 2014; Murawski et al., 2009). For example, Best et al. (2014) report that although baseline executive function predicted physical activity at program completion, improvements in executive function predicted sustained behavior change, specifically better adherence to physical activity over the following year. In several other interventions, increased restraint and decreased disinhibition were the only variables associated with weight loss at 12 weeks (Bryant et al., 2012; Butryn et al., 2009), and change in inhibition is reported as the strongest predictor of weight loss from 4 to 12 months (Butryn et al., 2009). These results hold important clinical implications, demonstrating the potential utility of executive function training in the context of health-behavior interventions.

While the evidence base is still small, a complex bidirectional relationship between executive function and weight-related health behaviors appears likely (Allan et al., 2011; Hall & Fong, 2013). Surprisingly few studies have implemented prospective designs to draw clear causal conclusions, therefore the mechanisms and directionality underlying this relationship remain somewhat unclear. Certain executive functions predict initiation of healthy behaviors, other executive functions moderate the relationship between intention and health behavior, and changes or improvements in executive performance, that may subsequently predict weight loss outcomes, are reported. Unfortunately, many of these studies were not conducted in the context of a weight loss intervention, therefore changes in weight or BMI were not measured as outcome variables. Given, however, that many of the eating patterns discussed above are associated with weight change, it is reasonable to posit that maintaining a healthy weight requires inhibition of desires to consume high-fat foods, and a consistent assessment of information relevant to the weight-loss goal at hand. To further explore the complexities of this relationship, we turn to an overview of the literature examining the impact of weight loss on executive function.

Impact of weight loss on executive functioning

Several studies have investigated whether interventions targeting caloric intake and weight loss might reduce the risk of cognitive decline typically observed in mid to late life, and lead to improvements in executive function as a result of decreased BMI. This line of research also raises interesting and important questions regarding the extent to which executive function is a viable target for intervention and whether brain structure or function might change as executive function skills are strengthened (Alvarez & Emory, 2006; Suchy, 2009).

Findings regarding the impact of weight loss on executive function are mixed. Few studies have implemented prospective designs to examine the impact of decreased calorie intake or weight loss on cognitive function, specifically executive performance, in obese samples. Several studies report significant negative associations between baseline BMI and cognitive function at follow-up (Cournot et al., 2006; Gunstad et al., 2010; Sabia et al., 2009; Wolf et al., 2007). In an observational prospective cohort study, Cournot et al. (2006) report that higher baseline BMI is associated with cognitive decline at 5-year follow-up, however no significant relationship is reported between *change* in BMI and *change* in cognitive ability, including measures of executive function.

Significant positive associations between weight loss and executive function have also been reported (Bryan & Tiggemann, 2001; Butryn et al., 2009; Green et al., 2005; Gunstad et al., 2010; Halyburton et al., 2007; Siervo et al., 2012; Veronese et al., 2017; Wing et al., 1995). Findings from longitudinal behavioral weight loss interventions generally suggest significant improvements to overall executive function as a result of weight loss (ranging from 28-days to 12-week follow-up), however due to the range of functions measured (e.g., inhibition, set shifting ability), executive function variables impacted by successful weight loss are not uniform across studies (Bryan & Tiggemann, 2001; Siervo et al., 2012; Wing et al., 1995).

Finally, evidence of null or negative effects of weight loss on executive function, in longitudinal behavioral weight loss and dietary interventions, is reported throughout the literature (Bryan & Tiggemann, 2001; Cheatham et al., 2009; Espeland et al., 2014; Green et al., 2005; Halyburton et al., 2007; Martin et al., 2007). Negative impacts of weight loss on executive function are often attributed to the finite availability of cognitive resources, and the significant amount of cognitive control utilized during caloric restraint and preoccupation with weight loss and/or body image (Siervo et al., 2011). For example, as participants allocate cognitive resources to initiating healthy behaviors like physical activity, and daily self-monitoring of food intake, they may have fewer cognitive resources to allocate towards restraint or avoidance when presented highly palatable snack options. Some studies report that working memory and planning ability are negatively impacted by weight loss (Cheatham et al., 2009; Green et al., 2005), while others report no significant impact of weight loss on executive function ability (Espeland et al., 2014; Halyburton et al., 2007; Siervo et al., 2012).

While the scope of this review does not allow for a comprehensive summary of findings from the extant bariatric literature, the magnitude and rate of weight loss outcomes observed post-operatively may serve to elucidate, and perhaps augment, potential remediating effects of weight loss on executive dysfunction that non-surgical interventions have yet to demonstrate (Handley et al., 2016; Spitznagel et al., 2015). Findings indicate that bariatric surgery is associated with improved neurocognitive outcomes, including executive function, at short-term (12 weeks) and long-term (3 years) follow-up (Alosco et al., 2014; Handley et al., 2016). Furthermore, executive function performance has been shown to predict BMI 12 months post-surgery (Spitznagel et al., 2013b) and, adjusting for baseline cognitive function scores, poorer cognitive performance at 12 weeks post-surgery predicted reduced weight loss at 36-month follow-up (Spitznagel et al., 2014, 2013a, 2013b). Finally, a recent review of 18 bariatric studies reported change in brain activation following surgical weight loss, specifically associated with improved cognitive control (Handley et al., 2016).

This body of literature also addresses potential physiological mechanisms underlying the relationship between weight loss success and executive function. Specifically, the resolution of comorbidities associated with executive dysfunction (e.g., sleep apnea, type 2 diabetes, and hypertension), metabolic regulation (e.g., reduction in insulin resistance), and changes in neurohormone levels (e.g., leptin and ghrelin) significantly predict improved executive function performance 1 year post-surgery (Spitznagel et al., 2015). Additional research is needed to examine whether the executive function benefits exhibited following initial weight loss, whether surgically- or behaviorally-induced, are better sustained when weight regain is avoided.

Overall, findings on the impact of dietary content, weight loss, and decreased BMI on executive function among individuals living with overweight or obesity are somewhat equivocal. Several important limitations to the aforementioned findings should be noted. First, the length of interventions varied significantly from approximately 8 weeks to 8 years (Espeland et al., 2014; Halyburton et al., 2007). A variety of diets are also prescribed for weight loss purposes including low fat/low calorie diets (Butryn et al., 2009; Espeland et al., 2014; Siervo et al., 2011; Siervo et al., 2012; Wing et al., 1995), low carbohydrate diets (Halyburton et al., 2007), and low glycemic diets (Cheatham et al., 2009) that may differ in their cognitive complexity. It is unclear if and how different types of dietary restriction may impact executive function. Additionally, the stability of observed changes in executive function due to weight loss is unknown and has not been studied longitudinally. Whether these changes are permanent or transient will be an important point of future research and particularly crucial to intervention development.

No studies to date have used prospective or longitudinal designs to adequately examine executive function as a predictor of successful long-term weight loss maintenance in adults. Additionally, few studies have included a full, comprehensive executive function battery, but instead have focused on selective executive functions as they relate to weight-specific behavior. Given the literature reviewed thus far, and what is known regarding behavioral and lifestyle characteristics of successful "maintainers" (Peirson et al., 2015; Phelan et al., 2009; Teixeira et al., 2010, 2015; Thomas et al., 2014; Wing & Phelan, 2005) it is not only reasonable, but necessary, to construct a conceptual model of the impact executive function might have on successful weight maintenance.

A new conceptual framework for an executive function-weight loss maintenance model

Several models hypothesizing the role of executive functioning in obesity or initial weight loss have been published (Jauch-Chara & Oltmanns, 2014; Raman et al., 2013; Sellbom & Gunstad, 2012) however, these models do not map executive functions onto the specific behaviors associated with WLM success and/or the known barriers to WLM. Developing such a model is imperative in guiding future research, particularly longitudinal designs, that addresses the nature and directionality of the executive function-WLM relationship using well-informed hypotheses. Additionally, such a model provides a framework from which researchers and clinicians might begin to consider the impact of executive ability beyond neuropsychological assessment, as it applies to the treatment and challenges of successful and sustained health behavior change.

The aforementioned findings by Miyake et al. (2000) outlining distinct core executive functions are crucial in developing and conceptualizing a novel executive function-WLM model, as they not only demonstrate that executive function has the potential to impact WLM in at least three distinct ways, but that cognitive processes underlying these relationships are likely interrelated and may uniquely impact one another. It is clear that behavioral and psychosocial variables associated with initial weight loss are distinct from those associated with WLM, and that the influence of executive function on weight loss differs based on the specific weight-related behavior in question (Allan et al., 2011; Allom & Mullan, 2014). It is therefore conceivable that, in a similar fashion, executive functions might differentially impact one's ability to engage in and sustain behaviors associated with successful weight loss maintenance versus those associated with initial weight loss. Furthermore, the impact of specific executive functions may differ between different weight maintenance behaviors.

Fundamentally, a conceptual executive function-WLM model might propose that executive function, as a resource that facilitates self-regulatory processes (Hofmann et al., 2012), impacts or predicts health outcomes via distinct health-related behaviors (see Fig. 1). Specific behaviors associated with successful weight loss or WLM may act as mediators through which executive function impacts individual differences in the ability to maintain weight loss over time. In order to outline such a model, it is important to first consider the three core components of executive function previously mentioned: shifting, updating, and inhibition (Miyake et al., 2000), and subsequently consider the specific health behaviors, or mediators, uniquely associated with WLM (Byrne, 2002; Elfhag & Rössner, 2005; Svetkey et al., 2008; Teixeira et al., 2010, 2015; Thomas et al., 2014; Williams et al., 1996; Wing & Phelan, 2005).

Updating is defined as the ability to code and monitor new information as it becomes relevant to the goal at hand. Updating allows for active manipulation of relevant information in working memory (Miyake et al., 2000). Planning is a behavior associated with successful WLM and likely to be impacted by updating ability. Planning ability ensures dietary, exercise, and other weight management goals are more likely to be met in novel situations when advanced preparation of healthy meals is not feasible (e.g. restaurant eating or attending social events with novel food choices). Individuals who set goals in advance, or

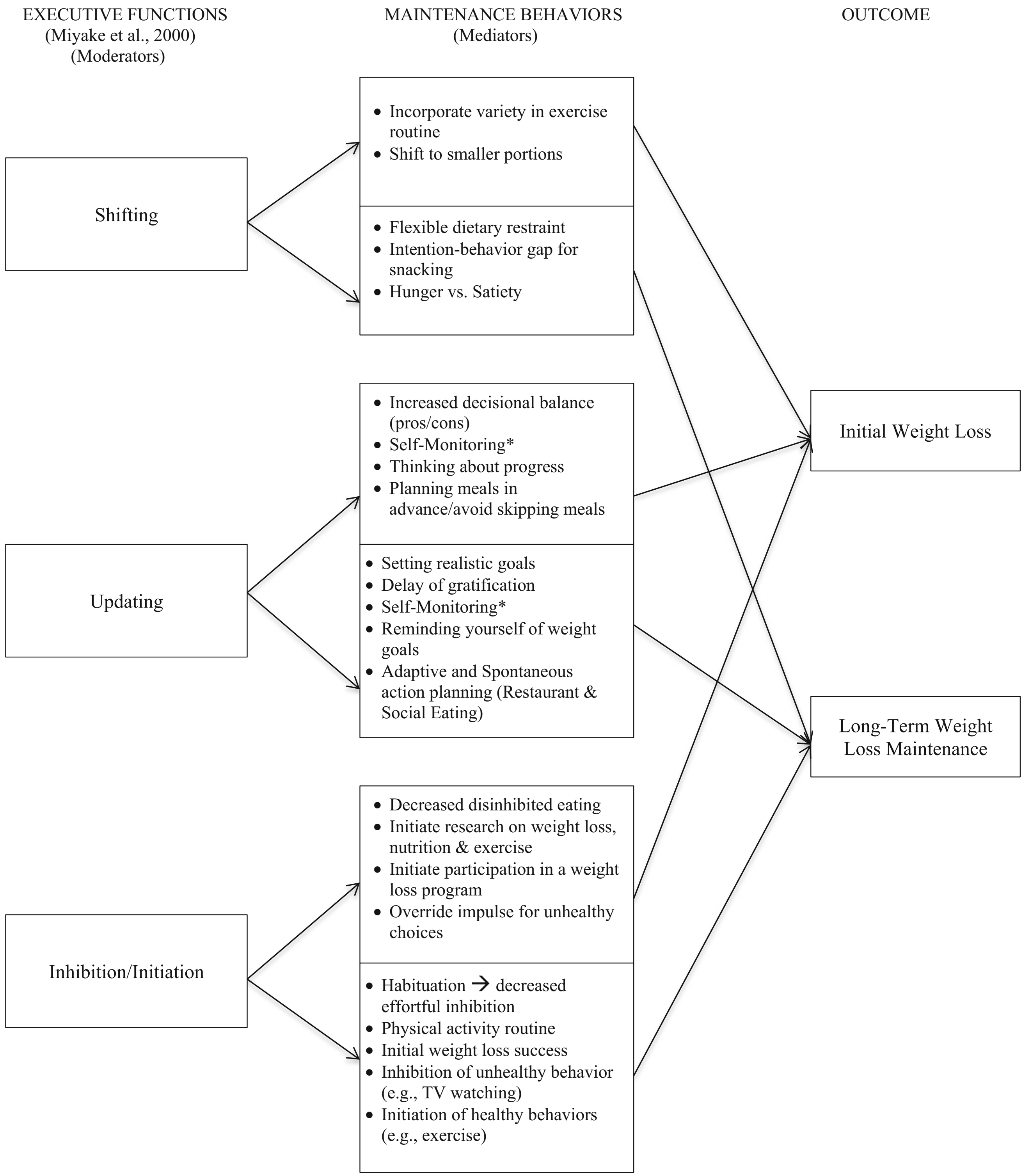

Fig. 1 A preliminary conceptual model of the impact of executive functions on successful weight control. The model outlines the potential role of executive functions as moderators of specific behaviors implicated in two distinct phases of the weight management process: (1) initial weight loss and (2) long-term weight loss maintenance. *Behaviors implicated in both initial weight loss and weight loss maintenance

have practice in spontaneous action planning, are likely better suited to make dietary choices that are concordant with WLM goals. Meals must also be planned to meet specific nutritional needs while fitting specific dietary restraints. Additionally, successful maintenance requires significant and consistent monitoring of potential dietary slips to detect and compensate for small weight fluctuations before they become significant regains. Consistent self-monitoring practices have been documented as one of the strongest predictors of WLM, including daily self-weighing, calorie tracking, and physical activity (Anderson et al., 2001; Barte et al., 2010; Bond et al., 2009; Butryn et al., 2007; Dombrowski et al., 2014; Peirson et al., 2015; Phelan et al., 2009; Teixeira et al., 2010). Self-monitoring can reasonably be considered a process closely related to updating ability. Goal-relevant information obtained through the monitoring process is precisely the information that must be actively manipulated to help individuals assess which health behaviors promote weight maintenance, and which behaviors lead to weight fluctuations or gains.

Shifting, also referred to as "task shifting" or attention shifting, is defined as the ability to disengage from goal-irrelevant tasks or activities and subsequently engage in a new, relevant task set. Shifting from one task to the next also requires overcoming interference from the previous task, and avoiding perseverations or repeating behaviors that no longer fit the new goal (Miyake et al., 2000). As it relates to WLM, task shifting allows individuals to temporarily disengage from self-regulatory behaviors that are consistently enacted to flexibly accommodate changing environmental or social influences. In other words, shifting may allow those attempting maintenance to manage short-term and long-term weight-related goals by making adaptive decisions as their environment and goals fluctuate over time. Research indicates that individuals engaging in weight loss or weight loss maintenance, who allow themselves to temporarily disengage from strict dietary restraint without feeling remorse, thereby approaching the WLM process with "flexible dietary restraint", are more successful maintainers than those with "rigid restraint" patterns (Hofmann et al., 2012; Kiernan et al., 2013; Teixeira et al., 2010). As noted previously, research also suggests that task switching and flexibility predict intention-behavior gaps in snacking behavior (Allan et al., 2011). It should be noted that there is a fine line between adaptive methods of shifting and complete disengagement from the goal at hand (i.e. regain). Therefore, employing balanced flexibility likely recruits a host of cognitive resources that undoubtedly overlap with other executive functions such as inhibition, control, and planning.

Finally, inhibition, formally defined as the ability to override a dominant, automatic, or prepotent response, is highly implicated in initial weight loss, and certainly contributes significantly to sustained WLM. Despite an abundance of evidence that inhibition and initiation predict distinct dietary behaviors, it is crucial to consider how inhibition and initiation might predict WLM. Inhibition plays an important role in overriding habits and impulses to consume high-fat palatable foods (Hofmann et al., 2012). Elfhag and Rössner (2005) report that compared to individuals who regain, successful maintainers demonstrate less dietary fat intake, reduced frequency of snacking, and adaptive management of cravings. Successful maintainers initiate more health behaviors, including consistent physical activity, and consumption of fruits and vegetables. Notably, initiation appears to be one of the most frequently studied executive functions in the obesity literature, yet many studies have measured dietary restraint and disinhibition using the self-report Three Factor Eating Questionnaire. When studies have measured executive function with neuropsychological tests the Stroop or Go-No-Go tasks are cited most frequently. Several studies report that successful weight loss maintainers exhibit slowed reaction time and greater interference on Stroop paradigms using high-fat food cues compared to participants with obesity and normal weight controls (Allan et al., 2011; Phelan et al., 2011). These findings suggest that maintainers may be employing greater executive resources to resist high fat foods, leading to increased salience of palatable food cues, however the directionality and predictive nature of inhibition on maintenance cannot be established from cross-sectional designs. The interaction between implicit preference for snack foods and baseline response inhibition also predicts weight regain over 1 year, such that participants with lower response inhibition gain more weight (Daly et al., 2015; Nederkoorn et al., 2010). The impact of inhibition on successful maintenance over time remains to be studied.

Mapping core executive functions onto behaviors known to be associated with, and *predictive* of WLM, is a necessary step in further understanding the cognitive underpinnings of long term weight loss maintenance from a neuropsychological perspective. Research by Wing and Phelan (2005) suggests that successful maintainers engage in the aforementioned behaviors (or mediators) to a greater extreme than their always normal-weight counterparts, indicating that these behaviors are a crucial focus for future executive function research. Evidence of shared variance between the components of executive function indicates that future research in this area must also consider the extent to which executive functions might interact or impact one another, and the influence such interactions might have on WLM outcomes.

Treatment implications and future directions

Integration of health and neuropsychological approaches to weight control holds undeniable implications for clinical practice. The challenge of understanding successful weight loss maintenance requires a closer look at the cognitive underpinnings associated with the weight management process. The literature outlined thus far provides sufficient evidence to suggest that adults with obesity exhibit deficits in executive function, and that executive performance has clear connections to skills that are necessary to succeed in weight management and long-term maintenance.

Weight loss maintenance has become an important focus for intervention design and implementation. Behavioral weight loss programs focusing on both diet and physical activity resulted in a −1.56 kg difference at 12-month follow-up compared to controls (Dombrowski et al., 2014), however these interventions clearly lack elements of cognitive or executive function training. In part, this may be due to difficulty appropriately incorporating individual-level, biological, or neurocognitive correlates of health behavior (e.g., executive function), into large-scale treatment studies. If executive function can be trained in adults with obesity, and training in one realm of executive function may generalize to other executive functions, there exists immense clinical potential that will directly impact the development and design of WLM interventions. In fact, preliminary evidence suggests that cognitive training, and some executive function-specific interventions, have successfully promoted health behavior change in other clinical populations, including binge eating disorder (BED), breast cancer patients, pediatric overweight and obesity, and ADHD patients (Grilo & Masheb, 2005; Halperin et al., 2013; Hannesdottir et al., 2014; Juarascio, et al., 2015; Kesler et al., 2013; Tamm et al., 2014; Verbeken et al., 2013).

Aforementioned findings from the bariatric literature, and low rates of successful weight loss maintenance demonstrated in standard behavioral interventions, speak to the importance of incorporating sensitive standardized measures of executive function to capture changes in executive function over time. Neuropsychological batteries that tap multiple executive functions and allow for both fixed and flexible testing approaches, include the Neuropsychological Assessment Battery (NAB) (White & Stern, 2003), the Delis-Kaplan Executive Function System (DKEFS) (Delis et al., 2004), and the NIH Toolbox Cognition Battery (Weintraub et al., 2013). Careful consideration should also be given to the idea that engagement of executive function may be context specific, such that high executive function scores on standardized neuropsychological measures may not translate directly to successful implementation of weight management behaviors. A true understanding of the impact of executive function on successful weight loss maintenance should include measures of executive skills as they apply specifically to the behavior of interest, and may require the development of novel measures tapping specific weight loss maintenance skills (e.g., eating-specific impulsivity) (Liang et al., 2014). Our model may provide a preliminary foundation on which to conceptualize and further develop weight management-specific measures of executive function.

Several studies suggest training cognitive behavioral (CBT) and cognitive remediation (CRT) strategies assist in weight management and improve symptoms of BED (Cooper et al., 2010; Grilo & Masheb, 2005; Raman et al., 2014). Family members of participants enrolled in a CBT-based weight loss program have also exhibited improved food choices and increased motivation for physical activity (Grilo & Masheb, 2005; Rossini et al., 2011). Such findings indicate that targeting cognitive processes more generally, such as cognitive restructuring, as they relate specifically to weight-control behaviors, may be an important and viable treatment strategy to fortify behaviors implicated in successful maintenance (e.g., increased physical activity). These findings also indicate that targeting behaviors that engage executive functions specifically, within the context of a traditional weight loss program, may be equally promising. In fact, there is interesting, though preliminary, evidence to suggest that executive functions can be improved if trained early in children. Particularly among children exhibiting the greatest difficulties in executive skills, early training holds the potential to significantly impact a child's academic success, mental health, and physical health trajectories later in life (Diamond & Lee, 2011; Diamond et al., 2016). Perhaps most encouraging are findings from a recent study conducted with adolescents receiving inpatient treatment for morbid obesity. Results demonstrate that children with obesity who participate in a computer-based executive function training game show significantly greater improvements in WLM and executive function skills up to 8-weeks post-inpatient treatment compared to children with obesity in the non-executive function training group. Notably, WLM benefits were no longer observed at 12-week follow-up (Verbeken et al., 2013). Few studies to date have examined the impact of executive function training over time in a population with overweight or obesity, however recent longitudinal interventions and ongoing trials have begun to focus on training self-regulatory skills specific to the weight loss process (Forman et al., 2016; Miller et al., 2012; Warschburger, 2015; Wing et al., 2016).

Paucity of executive function-training interventions for adults, particularly in the context of weight control interventions, leaves many questions for future research regarding the efficacy of such training in the context of standard behavioral weight loss programs. One crucial question for future intervention design is whether executive functions are malleable among adults, and if so, whether there are critical windows for intervention across the lifespan. It may also be important to consider whether variability in mid-life executive performance impacts individual efforts towards successful weight loss maintenance.

As executive function-training interventions are designed with the goal of improving weight loss maintenance outcomes, participants might also be encouraged to practice specific cognitive skills that strengthen aspects of executive function closely tied to the WLM process. Participants should be aware that situations in which executive resources are in high demand or become depleted might lead to plateaus or changes in weight loss or WLM progress. Appelhans et al. (2016) recently proposed a neurobehavioral intervention model for targeting and curbing temptation in the context of weight control programs. Importantly, the neurobehavioral model outlined by Appelhans et al. (2016), serves to highlight the crucial role that executive functions play in temptation prevention and temptation resistance by organizing intervention strategies by how taxing or demanding each strategy is on executive capacity. Such a model is complementary to our own executive function-WLM model, as it lends strong evidence for the need to map *specific* WLM behavioral strategies onto *specific* executive skills, in order to design and implement similar interventions, not only for temptation avoidance, but specifically tailored towards improved long-term weight loss. As research in the field progresses, and novel intervention approaches consider incorporating executive function training, understanding and distinguishing executive functions that are most responsive to training and those executive functions most essential for successful WLM will be crucial. As noted by Allom and Mullan (2014), superior executive function does not necessarily lead to expertise and ease across all health-related behavior change.

Our model attempts to bridge important gaps between neuropsychological and behavioral approaches to the weight loss maintenance dilemma, in the hopes of providing novel perspectives and provide a framework for the development and implementation of novel treatment approaches. Given the purpose and extent of this model, there are several important areas of successful weight maintenance that fall beyond the scope of this framework. We acknowledge that there are strategies proven to predict and assist in successful WLM, including strong social support networks, psychosocial stressors, and individual coping strategies that are not addressed or accounted for in our model. For example, research suggests that adults living with obesity are more likely to be depressed than non-obese adults, 43% of U.S adults with depression are living with obesity, and in every age group, women with depression are more likely to have obesity than women without depression (Pratt & Brody, 2014). This is problematic given that the majority of weight-related interventions implement strict exclusion criteria including history of psychiatric comorbidity, and therefore results may not generalize to community samples. From a cognitive perspective, assessing depression history in patients entering a WLM intervention is essential given the well-documented impact of major depressive disorder (MDD) on cognitive and executive function (Lam et al., 2014; Snyder, 2013). Psychiatric comorbidities will likely influence individuals' executive function performance, but the exact nature of such influences, combined with initial weight loss, on maintenance success, is unclear.

Additionally, the interaction and relationship between other health behavior changes, like physical activity, that are known to impact both cognitive function and contribute to successful long term maintenance should be carefully considered. In adults, the positive impact of physical activity on executive function and general cognitive function is well documented (Chan et al., 2013; Daly et al., 2015; Hayes, et al., 2014; McAuley et al., 2013). The vast majority of weight loss and WLM programs implement physical activity regimens, therefore the influence of exercise on executive function and WLM should be clearly distinguished and separately examined from influences of physical activity and executive function on WLM concordantly.

Conclusion

True integration of behavioral and neuropsychological approaches to weight management will first require the establishment of field-unifying theories in guiding future research on executive function and WLM. Despite evidence linking executive function to general health outcomes, cognitive models of health behavior change are largely dominated by social-cognitive approaches, and few neuropsychological theories have guided weight management research. Weight-related health behavior change, particularly WLM, is inarguably a complicated process with many biopsychosocial contributors. As evidenced by this review, WLM may be uniquely challenging due to the significant amount of high-order neurocognitive resources recruited over extended periods of time. Despite increased awareness of the difficulties associated with WLM, a true understanding of successful, long-term change continues to elude the obesity field. The challenge of improving maintenance outcomes calls for novel research and clinical approaches. Acknowledging neuropsychological mediators and moderators of WLM is crucial in moving the obesity field toward increased integration and impactful treatment designs. Cognitive processes defined as executive function appear to be particularly integral to the weight control process, and are therefore an excellent target for future WLM research.

A focus on neuropsychological factors in weight control and WLM, using a compilation of self-report, task-based, and neuroimaging measures will allow for neuropsychological approaches to be incorporated into traditional gold-standard behavioral treatment. Increased collaboration will also allow health psychologist and neuropsychologists to answer many of the remaining questions regarding the immense potential of executive function-based training on sustained health-behavior change.

Currently, research on the executive function-WLM relationship is sparse. Few attempts have been made to implement task-based measures of executive function in prospective, longitudinal obesity studies, and discussion of executive function-based training in the context of weight loss and WLM intervention is newly emerging. Current cross-sectional designs allow for conclusions that are, at best, suggestive of causal executive function-WLM relationships. Innovative approaches are necessary to progress our knowledge of successful weight loss maintenance in the obesity field, but will require a willingness to integrate diverse and novel perspectives into current weight control treatment and research.

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Compliance with ethical standards

Conflict of interest Katelyn M. Gettens, and Amy A. Gorin declares that they have no conflict of interest.

Human and animal rights and Informed consent All procedures followed were in accordance with ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. Informed consent was obtained from all patients for being included in the study.

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