Overweight and Obesity: The Role of Executive Functions in excessive body weight

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Sommario

Abstract

The increasing incidence of people who are affected by overweight or obesity represents one of the main worldwide health problems. Accordingly, to deep the possible causes or exacerbating factors related to the increasing body weight is relevant. In the last years, many studies have focused on the relationship between body weight and cognitive processes. However, few studies focused on the relationship between overweight in the absence of pathological conditions and Executive Functions (EFs). This study is aimed to detect some aspects of the relationship between EFs and overweight in the general population. A systematic review of the literature (Chapter 1) analyzed cross-sectional and longitudinal studies to verify a possible causality between these variables. In the following chapters, some experimental studies have deepened aspects that emerged from the literature as under-examined.

In both theoretical and experimental sections, the overall work has highlighted the need to approach executive functions in overweight and the related overeating behavior, confirming an association between specific EFs and overweight conditions during different developmental stages. In addition, a moderate role of food stimuli in influencing executive performance emerged.

Introduction

Overweight and obesity represent priorities of welfare and public health policies (WHO, 2016; 2020). Obesity is associated with high levels of morbidity and mortality, representing a risk factor for many chronic diseases such as hypertension (Kotis et al., 2015), diabetes (Hauner, 2017), and cardio-respiratory diseases (Littleton, 2012). Moreover, it is related to psychopathologies - such as anxiety disorders and depression (Gariepy et al., 2010; Carey et al., 2014) - and social difficulties - such as bullying and social isolation (Kolotkin et al., 2001), causing a general decreasing in quality of life (Janssen et al., 2004; Kolotkin et al., 2001).

The most frequent factors associated with the excessive increase in body weight are maladaptive eating behaviors and inadequate physical activity (Prentice, 2001; Dubbert et al., 2002), which allow a chronic imbalance between individual needs and energy acquisition (Yumuk et al., 2015). Besides, it appears to be related to increased cognitive impairment in the elderly (Beydoun et al., 2014).

The strong economic and health impact of obesity is noticeable. In 2014, about 600 million adults (38% of the population) were affected by obesity (with a body mass index higher than 30) and about 42 million children (17% of the population) aged between 5 and 18 showed overweight/obesity conditions (Yumuk et al., 2015; Gettens & Gorin, 2015; Odgen et al., 2014). Despite the prevention policies, this trend is continuously increasing, and it is expected that in 2030 about 60% of the world population will reach critical values of BMI (Kelly et al., 2008; WHO, 2016). Italy is the European country with the highest prevalence of overweight and obesity (14% of the general population) (WHO Regional Office for Europe, 2016; Hernandez-Quevado & Rechel, 2018).

For these reasons, in the last years, an attempt to structure programs to prevent obesity and promote healthy eating behaviors and lifestyles has been developed (WHO, 2015). These programs are focused on reducing the risk of the onset and maintenance of overweight and obesity, promoting good dietary habits and healthy lifestyles (WHO, 2018). However, they do not appear to be able to reduce this negative trend. These failures can probably be due to the over-stimulation of food products, representing reward stimuli for the individuals (Volkow et al., 2011; Shin et al., 2011). Identifying the aspects that could increase the effectiveness of these programs and promote the long-term success of the weight-management interventions is important.

Accordingly, challenges of modern science toward obesity are: 1) to implement effective treatments for the reduction of obesity risks, 2) trying to reduce body weight in order to improve quality of life and overall health, and 3) reducing the percentage of failure in maintaining the success in weight loss, often associated with traditional weight loss programs (e.g., diets, physical activity, bariatric surgery; Wing & Phelan, 2005; Galioto et al., 2016).

In the first chapter of this manuscript, a systematic review of the literature, developed according to the PRISMA statement, was aimed to detect the point of view of the scientific community about a specific field of cognitive sciences focused on body weight and eating behavior, i.e., the relationship between the Executive Functions (EFs) and excessive body weight (considering both overweight and obesity). EFs are a pool of cognitive processes that influence the individual's behavior, determining their response to environmental stimuli and affecting emotional aspects (Myake et al., 2000; Diamond, 2003; Chan et al., 2008). The systematic review (Favieri et al., 2019) highlighted that EFs are associated with overweight and obesity.

EFs (Espy et al., 2004; Cragg e Gilmore, 2014) include monitoring and manipulating information in mind (working memory), suppressing distracting information and unwanted responses (inhibition), flexible thinking (shifting), planning of complex action (planning), and decision-making.

In eating behavior, alterations in EFs seem to be associated with maladaptive habits causing body weight increase (Hall and Marteau, 2014; Dhole et al., 2018). Cross-sectional studies confirmed that individuals with obesity tend to show higher deficits in inhibition, cognitive flexibility, decision-making, and planning than normal-weight people (Favieri et al., 2019; Yang et al., 2017). Longitudinal studies highlighted how the relationship between EF and overweight is characterized by a bidirectional pattern that emerges at some point in the life span. However, the studies did not identify a causal direction at the origin of the relationship between EFs and obesity. The bidirectionality is characterized on the one hand by a predictive role of EFs in determining weight variations (Smith and Robbins, 2013; Chen et al., 2017) and success in weight loss programs (Kulendran et al., 2017; Augustijn et al., 2018), on the other hand by an effect of the excessive body weight and related pathophysiological processes (e.g., chronic inflammation or alterations in the cerebral perfusion; Perry, 2004; Sellbom and Gunstad, 2012) on the impairment of EFs.

Generally, the studies confirmed the importance of intervening on EFs for increasing the effectiveness of weight loss programs. However, they did not clearly define the specific dimensions on which to intervene. Moreover, the inconsistent results about the link between overweight and obesity and EFs (Gonzales et al., 2010; Pignatti et al., 2006) are also reflected in the theoretical models trying to clarify this relationship (Wang et al., 2004; Davis et al., 2007; Arnow et al., 2005; Perry et al., 2004). Some theoretical models supported that obesity may depend on dysfunctions in mechanisms related to cognitive processes and EFs (Wang et al., 2004; Davis et al., 2007), while other models assume obesity as a cause of cognitive dysfunctions, including EFs (Perry et al., 2004; Sellbom & Gunstaf, 2012). According to both these views, neuroimaging studies have identified some neurofunctional alterations that could explain the relationship between EFs and the increase of body weight. Alteration in Dorsolateral Prefrontal Cortex (DLPFC) and dopaminergic gratification circuit (Gluck et al., 201; Shin et al., 2011) are highlighted in the condition of obesity. These areas are involved in the executive response and goal-directed behaviors, and their structural and functional alterations seem to be associated with overeating (Shin et al., 2011). Obesity appears characterized by a reduction of grey matter at the PFC level, and neuroimaging studies have shown that weight loss is related to an increase in grey matter in the same areas, associated with improved executive performance (Gluck et al., 2017). These findings might confirm certain reversibility of executive impairment related to the physiological changes in obesity, and they could indicate that an improvement in EFs may be the basis for the long-term success of interventions. Moreover, the improvement could reduce the risk of coppinitive impairment in old age, which in recent studies appeared to be associated with long-term consequences of excessive body adiposity (Gustafson, 2008; Beydoun et al., 2014).

An interesting theoretical model that could condense different variables involved in the excessive body weight could be the Emotional Eating Model (Roth et al., 1984), which considers food intake as a coping strategy that tries to restore order in the dysregulated emotional context by compensating for a negative affective state (Lazarevich et al., 2016). Individuals who show large food intake would not regulate their own emotions and manage the affective states adaptively, using food as an emotional regulator to help reduce situational stress, perceived as negative. Although this pattern is present in the general population, it appears to be more established in individuals affected by severe obesity, loss of control, and binge eating behaviors (Fischer et al., 2007; Goossens et al., 2009; Macht, 2008). Emotional eating seems to be associated with a reduction in mood and high depressive symptoms (van Strien et al., 2016), high impulsivity traits, and low inhibitory control (Jasinka et al., 2012), and alteration in working memory (Houben et al., 2016). It would be a behavioral pattern influenced by both cognitive and affective aspects, but few studies focused their attention on the interaction between these aspects.

According to these considerations, the importance of this research field is evident. In fact, until now, the research has not clarified the direction of the relationship between EFs and obesity, and it has not been able to identify whether and which executive mechanism is more involved in this relationship. Accordingly, this dissertation aims to clarify the relationship between EFs and excessive body weight in the absence of other medical or psychopathological conditions, and the nature of this relationship. This aim can help planning integrated interventions for the reduction and maintenance of body weight.

The subsequent studies reported the experimental studies conducted during the doctoral programs with the following goals:

1) to analyze the role of the food stimuli in influencing executive performances, highlighting further factors that could affect the relationship between overweight and EFs (Chapter 2). A sample of healthy young adults (starting from the first phases of overweight: BMI ≥ 25 and < 31Kg/m2), with no eating disorders or significant levels of overweight, was expected to confirm an association between executive tasks adopting food cues and body mass index. Few studies focused on this topic, and this study aimed to cover up this lack of evidence;

2) to define the relationship between EFs and excessive body weight in a healthy population in different phases of development (childhood, adolescence, early adulthood) (Chapter 3). Although the literature reports studies that have investigated the relationship between EFs and obesity in different age groups, there are no studies that have assessed this relationship across the age, as well no studies trying to identify the involvement of specific EFs in specific developmental phases. It was expected that excessive body weight would be linked to performances in the EFs task, regardless of age differences, in line with the studies which found differences between participants with obesity/overweight and normal weight both in young adulthood (Coppin et al., 2014; Pooja et al., 2014), childhood (Boozkurt et al., 2017; Wu et al., 2017) and adolescence (Kittel et al., 2017; Sweat et al., 2017). However, considering the development of EFs during

life span (Hall & Marteau, 2014), it was expected that specific Executive Domains would be involved in excessive body weight at different levels and in different ways during the life span;

3) to identify whether and what high-level EF, such as planning, and decision-making, are mainly involved in the relationship with excessive body weight (Chapter 4). In fact, although the literature agrees on the link between poor executive performance and obesity, the specific involvement of each EF has not been clarified, especially considering the most complex and integrate domains (Favieri et al., 2019).

The chapters of the thesis were structured as independent papers, following the typical format of scientific publications. For this reason, there will be some inevitable repetitions throughout the work to make the single papers clear and self-explanatory.

A final concluding paragraph will summarize the main results of this dissertation.

CHAPTER 1. The relation between excessive body weight and executive functions: a systematic review of cross-sectional and longitudinal studies

Introduction

Obesity and overweight, commonly defined as the accumulation of excessive body fat, are risk factors for many chronic diseases, such as hypertension (Jiang et al., 2016) and diabetes (Hauner, 2017) as well as musculoskeletal (McPhail et al., 2014) and respiratory problems (Littleton, 2012). The increase in body weight, associated with inappropriate food behaviors, appears to be also connected to many psychopathologies (e.g., anxiety disorders and depression; Carey et al., 2014; Carpiniello et al., 2009; Gariepi et al., 2010), emotional dysregulation (Casagrande et al., 2019) and social difficulties (e.g., bullying and social isolation; Kolotkin et al., 2001). Moreover, recent prospective studies showed an association between obesity in adulthood and cognitive impairment in old age (Sanderlin et al., 2017).

The most common risk factors for the increase in body weight are poor eating habits and a lack of adequate physical activity (NIH, 2019; Fru et al., 2017), which results in a chronic imbalance between the individual's needs and energy acquisition (Yumuk et al., 2015).

Conventionally, the overweight and obese classifications are made according to the body mass index (BMI; WHO, 2000), which considers the weight and height of a person, providing a quantifiable body mass. An excessive BMI increase can lead to a higher risk of premature death and a lower quality of life (WHO, 2000).

The prevalence of obesity and overweight has increased in recent years. In 2014, more than 1.9 billion adults were overweight (WHO, 2015); of these, 600 million were classifiable as obese. Regarding younger people, in 2013, it was estimated that about 42 million children and adolescents between the ages of five and 18 years, and about 12.4% of children below the age of five years, were overweight or obese (Yumuk et al., 2015; WHO, 2015). It is expected that around 60% of the world's population will reach critical BMI values by 2030 (Kelly et al., 2008).

Considering these data, investigating the predisposing and exacerbating factors of excessive body weight is necessary. In line with this need, recent studies focused their attention on the cognitive mechanisms involved in overweight or obesity (Forcano et al., 2018; Liang et al., 2014), such as the executive functions (Yang et al., 2018).

Executive Functions

Executive functions (EFs) is an 'umbrella term' (Chan et al., 2008; Damasio, 1995; Diamond, 2013; Elliot, 2003) that includes both complex cognitive processes— the resolution of new tasks, the modification of existing behaviors, the planning of new strategies for problem-solving, the sequencing of complex actions (Elliot, 2003; Funahashi, 2001), the inhibition of motor or automatic cognitive responses and the control of conflicting information (Diamond, 2013) — and lower-level cognitive processes, which allow thoughts and actions to be regulated and controlled during goal-directed behavior and involve different cognitive dimensions such as perception and sensation, memory and motivation, attention, reasoning and problem-solving (Pennington & Ozonoff, 1996).

Although there are various executive functions, many studies have focused on three specific processes (Diamond, 2013; Miyake et al., 2000): (i) Cognitive Flexibility (or Shifting), characterized by an attentional shift between tasks or between different mental operations; (ii) Working Memory (or Updating), which includes the updating and monitoring of mental representations in order to respond appropriately to external tasks or stimuli; and (iii) Inhibition, which consists of the voluntary inhibition of dominant or automatic responses for controlling behaviors, thoughts and emotions, as well as attentional aspects, in order to respond appropriately to the needs of goal-directed behavior (Diamond, 2013; Hofmann et al., 2012; Miyake et al., 2000).

Some authors (Chan et al., 2008; Grafman & Litvan, 1999) distinguish between two different groups of EFs: the 'cold EFs' and the 'hot EFs'. The first— which includes verbal reasoning, problem-solving skills, planning, attentional maintenance, cognitive flexibility, response inhibition, and control of conflicting information—is characterized by the absence of emotional processing of stimuli and tends not to generate emotional arousal (Chan et al., 2008). The second - which includes expectations of punishment-gratification, social behavior, and decision-making - is characterized by the presence of beliefs and desires and includes a strong emotional component (Chan et al., 2008). EFs, whether 'hot' or 'cold', play a crucial role in everyday working jointly, and both are necessary to direct our behavior. It is essential to underline that EFs are characterized by individual differences, which during life undergo multiple modifications (Jacques and Marcovitch, 2010; Hall and Marteau, 2014), as the reduction of cognitive flexibility and planning with aging (see Jacques and Marcovitch, 2010), or the alterations in inhibition in psychopathology (Nigg, 2000). These differences and changes can also be traced back to establishing healthy behaviors, such as eating habits (Hall and Marteau, 2014).

Executive Functions, Obesity, and Overweight

A recent review by Dohle and colleagues (2018) showed that some studies support the hypothesis that eating behaviors affect executive functioning, i.e., healthy eating habits promote the preservation of executive functions throughout life (Gonzales et al., 2010; Pignatti et al., 2006). Other authors are inclined to sustain the opposite view where the executive functions would be predictors of eating behaviors and, consequently, body weight changes. Accordingly, EFs deficits would cause an inappropriate approach to food and represent a trigger eating disorders and BMI changes (Dohle et al., 2018). These two viewpoints concerning the relationship between executive functions and eating behaviors are similar to those in the studies on the relationship between obesity and executive functions (Gonzales et al., 2010; Pignatti et al., 2006), and its complexity is also reflected in the theoretical models that have attempted to explain the nature of this relationship. However, it might be interesting to extend these types of studies because they could help identify some aspects of the increase in obesity and related problems.

Commonly, in the nutritional field, eating represents a process for producing the energy needed to sustain physiological processes and is controlled by a feedback process. This is the 'homeostatic' model (Hall, 2016). However, this model does not involve cognitive aspects. Other theoretical models (Arnow et al., 1995; Davis et al., 2007; Perry, 2004; Wang et al., 2004) postulate a relationship between obesity and cognitive functions; some studies affirm that obesity is a result of the dysfunction of mechanisms relating to cognitive and executive functions (Wang et al., 2004; Davis et al., 2007), while others assume that the physical implication related to the overweight cause cognitive dysfunctions (Perry, 2004; Sellbom & Gunstad, 2012).

Obesity as the Consequence of Executive Dysfunction

According to the 'Food Addiction' Model (Wang et al., 2004; Smith & Robbins, 2013), excessive body weight is due to a 'food addiction' because of a deficit in the reward system (Smith & Robbins, 2013). The attraction to hypercaloric food, high in sugar and fat, is associated with an activation of the limbic system areas (i.e., the amygdala, the insula cortex, and the orbitofrontal cortex; Goldstone et al., 2009). Nevertheless, excessive intake also depends on individuals' high sensitivity to these foods. Both the characteristics of food (e.g., taste, smell, and feature) and individual preferences and behavioral attitudes are influenced by experience, and genetic and metabolic factors (De Araujo & Rolls, 2004; Drewnowski, 1997) would determine the levels of sensitivity. The Food Addiction Model links addiction to a reduction in dopaminergic D2 receptors (Smith & Robbins, 2013), but the actual role of dopamine is still unclear.

Another model, which combines cognitive and behavioral aspects to justify excessive body weight is the Model of Altered Functioning of the Reward System (Davis et al., 2007). This model postulates a hypersensitivity to reward as a cause of the preference for hypercaloric foods (Davis et al., 2004; Davis et al., 2007; De Araujo & Rolls, 2004). This model links the risk of overeating behavior and resulting obesity to the tendency to prefer the immediate gratification of food (Davis et al., 2004). In accordance with this view, the Equilibrium Model (Chen et al., 2017) postulates that a balanced reward process is determined by the interaction between the inferior frontal gyrus and the orbitofrontal cortex, i.e., cortical areas involved in executive functioning (Chen et al., 2017; Wagner et al., 2013). The preserved integrity of these neurophysiological pathways appears to predict appropriate eating behaviors.

The Neuropsychological Model of the Genesis of Obesity proposed by Jauch-Chara and Oltmanns (2014) brings the excessive consumption of food back to the interaction between chronic stress and activation of the reward system. The eating of tasty foods, which is an immediate source of pleasure and energy, leads to the consolidation of maladaptive behaviors maintained over time (Jauch-Chara & Oltmanns; 2014).

All these models would converge in the Emotionally Driven Eating Model (Arnow et al., 1995; Dallman, 2010; Gianini et al., 2013; Pieper & Laugero, 2013; Ricca et al., 2009). According to the theories on emotional eating, the excessive consumption of food and the consequent increase in weight are driven by emotional dysregulation associated with high stress levels and resulting physiological arousal changes. All these aspects would be related to executive deficits, which induce individuals to seek homeostatic balance through food (Dallman, 2010; Pieper & Laugero, 2013). This model is considered the possible prodrome of Binge Eating Disorder (Arnow et al., 1995).

Obesity as the Risk Factor for Executive Functions

The Neuroinflammation Model (Perry, 2004) views obesity as a risk factor for executive dysfunction. According to this model, there is a strong connection between excessive BMI and the inflammatory process, an acclaimed neurodegenerative risk factor. Systemic inflammation, which negatively affects cognitive functions, including executive functions, would be due to the high adiposity related to obesity. An important role is played by C-reactive protein and interleukin (Bourassa & Sbarra, 2017).

Sellbom and Gunstad (2012) developed a preliminary model involving the interaction of obesity with other factors as possible cognitive impairment causes. Individuals affected by obesity would suffer from the atrophy of the frontal and temporal lobes and changes in blood flow and metabolism of the frontal lobes. These neurophysiological alterations lead to dysfunction in inhibitory control, which in conjunction with mood changes could exacerbate the maladaptive eating behaviors establishing a bidirectional relationship (Sellbom & Gunstad, 2012). Furthermore, clinical diseases such as hypertension and diabetes, and physiopathological factors such as insulin resistance, inflammation, and endothelial dysfunctions, would influence the relationship between obesity and cognitive impairment (Sellbom & Gunstad, 2012).

Despite having little empirical support, another model to consider is the Maintenance of Clinical Obesity (Raman et al., 2013), which focuses on the difficulty experienced by people affected by obesity in reducing their BMI. This wide-ranging model includes multiple dimensions associated with executive functions, such as emotion and mood dysregulation, as the determinants of persistent obesity.

Following what was reported above, investigating further the relationship between EFs and excessive body weight seems necessary. Some reviews tried to collect information about this relationship (Fitzpatrick et al., 2013; Vainik et al., 2013; Emery and Levine, 2017; Gettens and Gorin, 2017; Gluck et al., 2017; Yang et al., 2018), but they only confirmed the existence of a correlation between the variables nor clarifying the essence of this relationship, nor the causality. Identifying whether the EFs represent predictors of weight gain (Smith and Robbins, 2013; Chen et al., 2017) or consequences of the increased body weight (Perry, 2004; Sellbom and Gunstad, 2012) still represents an important goal in research.

Finally, another aspect to consider is the role of single executive domains in the relationship with overweight/obesity. Some studies identified impairment in specific EFs domains as decision-making, planning, and problem-solving (for a review, see Fitzpatrick et al., 2013) or inhibition (Gluck et al., 2017). However, generally, the studies did not well-defined the relationship between the single domain of EFs and excessive body weight (Vainik et al., 2013). However, to identify whether there is a specific EF or some EFs, which influences or are influenced by the excessive body weight could be useful both for the development of a theoretical model on EFs-overweight relationship and for the definition of risk factors related to excessive body weight or impairment in executive domains.

A review analyzing the relationship between EFs and overweight aimed to examine studies with different experimental designs (cross-sectional, longitudinal) could help identify a causal relationship between variables and understand how the interactions that emerged in cross-sectional studies change over time in longitudinal ones.

In our view, this represents a fundamental goal because it can be useful both for structuring interventions aimed at reducing risks related to excessive body weight and EFs impairment and contributing to developing more accurate theoretical models. Moreover, analyzing the causality between these variables could be a starting point to identify whether some executive domains are more involved than others in body weight changes.

Aims

This systematic review aimed to analyze longitudinal and cross-sectional studies investigating the association between EFs and obesity or overweight in the absence of chronic diseases or related eating disorders, trying to add knowledge about the nature of this relationship. Specifically, the aims of this systematic review are:

(a) to document the cross-sectional evidence between EFs and overweight/obesity, trying to identify the consensus on the presence of a relationship between EFs and excessive body weight;

(b) to see if any executive domain has been associated mainly with excessive body weight, considering both positive and negative results;

(c) to analyze longitudinal studies to assess the causality between EFs and the BMI, considering EFs eventually an outcome or predictor of increase in BMI. This review represents an attempt to systematize the studies on the relationship between EFs and overweight (Vainik et al., 2013; Emery and Levine, 2017; Yang et al., 2018). The inclusion of longitudinal studies by also considering different interventions to reduce weight (as in Thiara et al., 2017) could help clarify the nature of this relationship. The final aim of this review is to understand how approaching the problems related to excess body weight.

Methods

This systematic review was conducted according to the PRISMA-statement (Liberati et al., 2009; Moher et al., 2009), online registration of the protocol has not been provided.

Research Strategies

A systematic review was conducted using the international PubMed, PsycINFO, PsycArticles, MedLine databases. The following keywords were used: ‘Executive Function’, ‘Inhibition’, ‘Cognitive Inhibition’, ‘Selective Attention’, ‘Updating’, ‘Working Memory’, ‘Shifting’, ‘Cognitive Flexibility’, ‘BMI’, ‘Overweight’, ‘Obesity’, ‘Overeating’, ‘Diet’. The scripts used for the search are presented in Table 1.

All original, ‘full-text’ papers published in international, peer-reviewed journals up to 10 June 2018 were considered.

Table 1. Script for the systematic search.

	Script
Executive function and Obesity	("executive function"[MeSH Terms] OR ("executive"[All Fields] AND "function"[All Fields]) OR "executive function"[All Fields]) AND (BMI[All Fields] OR ("overweight"[MeSH Terms] OR "overweight"[All Fields]) OR ("obesity"[MeSH Terms] OR "obesity"[All Fields]) OR ("hyperphagia"[MeSH Terms] OR "hyperphagia"[All Fields] OR "overeating"[All Fields]) OR ("diet"[MeSH Terms] OR "diet"[All Fields]))
Inhibition and Obesity	(("inhibition (psychology)"[MeSH Terms] OR ("inhibition"[All Fields] AND "(psychology)"[All Fields]) OR "inhibition (psychology)"[All Fields] OR "inhibition"[All Fields]) OR (("Cogn Int Conf Adv Cogn Technol Appl"[Journal] OR "cognitive"[All Fields]) AND ("inhibition (psychology)"[MeSH Terms] OR ("inhibition"[All Fields] AND "(psychology)"[All Fields]) OR "inhibition (psychology)"[All Fields] OR "inhibition"[All Fields])) OR (Selective[All Fields] AND ("attention"[MeSH Terms] OR "attention"[All Fields]))) AND (BMI[All Fields] OR ("overweight"[MeSH Terms] OR "overweight"[All Fields]) OR ("obesity"[MeSH Terms] OR "obesity"[All Fields]) OR ("hyperphagia"[MeSH Terms] OR "hyperphagia"[All Fields] OR "overeating"[All Fields]) OR ("diet"[MeSH Terms] OR "diet"[All Fields]))
Working Memory and Obesity	(Updating[All Fields] OR ("memory, short-term"[MeSH Terms] OR ("memory"[All Fields] AND "short-term"[All Fields]) OR "short-term memory"[All Fields] OR ("working"[All Fields] AND "memory"[All Fields]) OR "working memory"[All Fields])) AND (BMI[All Fields] OR ("overweight"[MeSH Terms] OR "overweight"[All Fields]) OR ("obesity"[MeSH Terms] OR "obesity"[All Fields]) OR ("hyperphagia"[MeSH Terms] OR "hyperphagia"[All Fields] OR "overeating"[All Fields]) OR ("diet"[MeSH Terms] OR "diet"[All Fields]))
Cognitive Flexibility and Obesity	(Shifting[All Fields] OR (("Cogn Int Conf Adv Cogn Technol Appl"[Journal] OR "cognitive"[All Fields]) AND ("pliability"[MeSH Terms] OR "pliability"[All Fields] OR "flexibility"[All Fields]))) AND (BMI[All Fields] OR ("overweight"[MeSH Terms] OR "overweight"[All Fields]) OR ("obesity"[MeSH Terms] OR "obesity"[All Fields]) OR ("hyperphagia"[MeSH Terms] OR "hyperphagia"[All Fields] OR "overeating"[All Fields]) OR ("diet"[MeSH Terms] OR "diet"[All Fields]))

Eligibility Criteria

All the studies investigated the relationship between EFs and excessive body weight. Studies including at least one group with overweight or obesity, classified through the international criteria as BMI (World Health Organization, 2000) and BMI percentiles (Flegal et al., 2002), and investigating at least one EF were included. Furthermore, both cross-sectional and longitudinal studies were considered and analyzed separately. For the selection of the articles, the following inclusion criteria were used: (a) academic articles published in international, “peer-reviewed” journals; (b) studies written in English; (c) studies on humans with overweight or obesity (BMI higher than 25) at various levels of severity; (d) studies using cognitive tasks to assess EFs; (e) studies including participants aged between 5 and 70 years; (f) cross-sectional and longitudinal studies; (g) studies including different interventions to reduce body weight (bariatric surgery, cognitive remediation therapy, weight-loss programs that included diets, or physical activity); (h) studies including other psychological variables related to EFs and body weight.

The following exclusion criteria were applied: (a) brief reports: these types of articles were excluded because, after a preliminary analysis of them, it was observed that the information reported was too general; (b) studies examining participants with binge eating disorder or other eating disorders; (c) studies focusing on cognitive functions other than executive ones; (d) studies analyzing EFs through self-report questionnaires; (f) studies on obesity of metabolic origin or caused by other medical condition; (g) studies considering overweight in psychopathological or psychiatric conditions (e.g., depression, schizophrenia, ADHD, etc.). Moreover, for cross-sectional studies, the absence of a normal-weight control group to compare executive functioning was an additional exclusion criterion. For the longitudinal researches, both observational and experimental studies were included.

Additionally, in both cross-sectional and longitudinal studies, differences between groups (with normal-weight and overweight) or different assessment times (pre, post, follow-up) were mainly commented, although regression analyses were also considered. Correlational studies were excluded if the method did not include different BMI conditions (including both normal-weight and overweight individuals).

Data Collection Process

In accordance with PICOS (Liberati et al., 2009), the authors extracted information about participants (age, BMI, gender) in both control groups and overweight/obese groups, methods (executive task adopted), and main results observed in the EFs tasks.

According to the aims of this review, for the cross-sectional studies, all the results concerning comparisons between overweight/obese groups and normal-weight groups on a cognitive task that assessed one or more EFs were analyzed. All the results concerning the analysis over time of participants with excessive body weight were examined for the longitudinal studies, including weight and executive functioning changes following either weight-loss programs or cognitive training. The characteristics of the studies are shown in Tables 3, 4.

Quality Assessment

A quality assessment analyzed the eligibility of each article by detecting the quality of the studies. This process was aimed to reduce the risk of bias selection and was conducted using a six-point checklist created explicitly for the screening of the studies of this review. For each point, a maximum score of two (high-quality) could be awarded per article: a score of zero corresponded to a low-quality index, a score of 1 to a medium quality index, and a score of 2 to a high-quality index. To derive an overall quality score of the study, the mean score of each study was multiplied by 100. in line with other qualitative analyses (e.g., Varkevisser et al., 2019), studies with a score <75% were considered with high quality. The systematic review excluded studies with very low quality (lower than 50%). Table 2 shows the six-point quality assessment checklist. Tables 3, 4 reported the quality assessment for each selected article.

Table 2. Checklist for quality assessment

1) The use of standardized executive tasks*.	0= no standardized tasks; 1= use of some non-standardized tasks; 2= use of all standardized tasks.
2) Controlling of psychological (e.g. depression, anxiety, emotional dysregulation) and physiological variables (e.g., blood values, hormonal and inflammatory aspects).	0= no control of variables; 1= control of psychological or physiological variables; 2= control of both psychological and physiological variables.
3) The use of international guidelines for BMI classification.	0= no international guidelines; 1= shared guidelines (i.e. CDC); 2= international guidelines.
4) Quality of the method description (about executive variables).	0= procedures and assessment tools are not well indicated; 1= procedures and assessment tools are partially described; 2= procedure and assessment tools are well described.
5) Quality of results description (about executive variables).	0= executive functioning is not included in the results; 1= executive functioning is partially included in the results; 2= executive functioning is included in the results.
6) Quality of discussion and conclusion (about executive variables).	0= executive functioning is not included in either discussion or conclusion; 1= executive functioning is not well included in discussion and conclusion; 2= executive functioning is included in both discussion and conclusion.

* Behavioral tasks widely used in literature for the analysis of a specific executive functions.

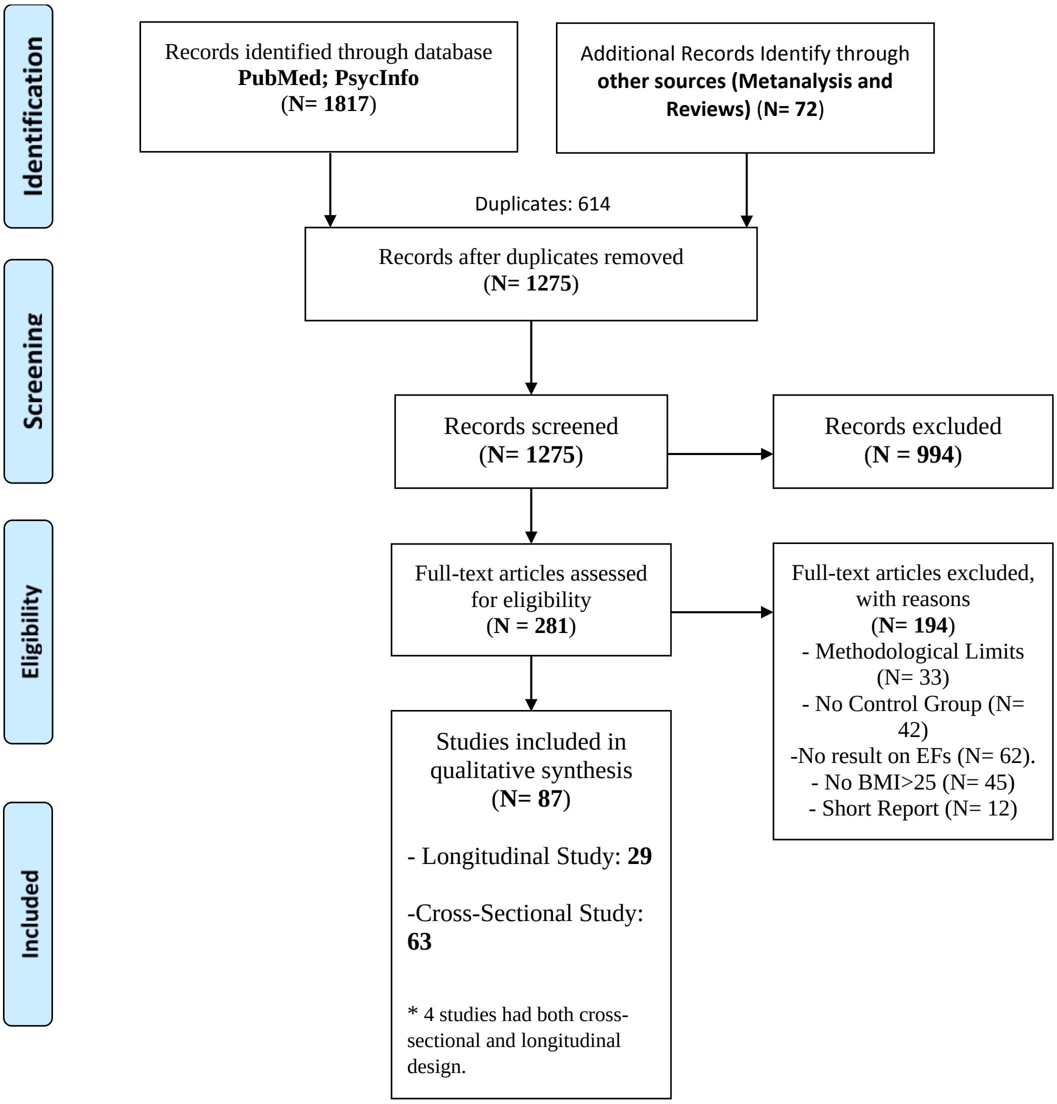
Results

Study Selection

The initial search produced 1,817 articles. After excluding 614 duplicates, 922 articles were rejected according to an analysis of both title and abstract, leaving a final total of 281 studies to be reviewed and subjected to the quality assessment. At the end of the review process, 88 articles remained. The flow chart (Figure 1) shows the study selection process, including the number of studies found, the assessment process, and the reasons for excluding the articles.

The 88 selected articles were categorized according to the type of experimental design. Sixty-three studies used a cross-sectional design, and twenty-eight studies used a longitudinal design (see Tables 3, 4). Three studies (Deckers et al., 2017; Demos et al., 2017; Vantieghem et al., 2018) used both cross-sectional and longitudinal designs. These studies considered the differences between participants with normal-weight and participants with overweight or obesity and analyzed the differences in executive performances during the time. For this reason, they were considered in both sections of the review.

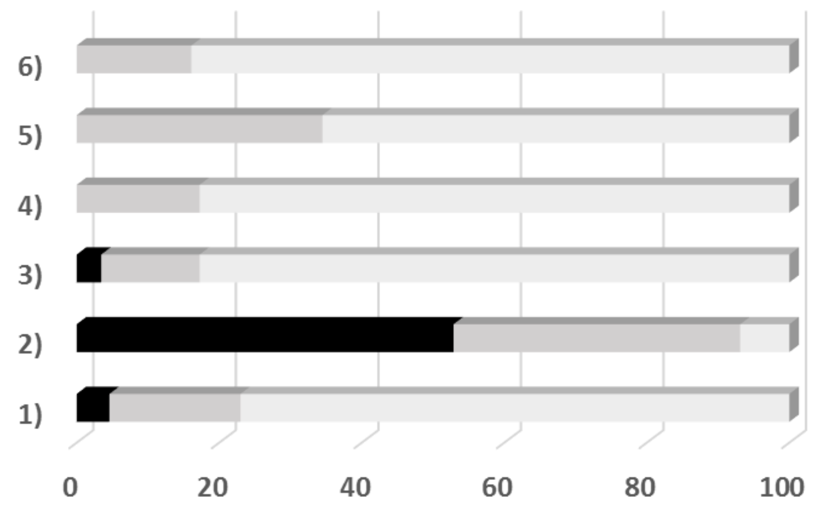
Figure 1. Flow chart of the systematic search



Quality Assessment for Risk Bias

Seventy-nine percent of the studies (N = 70) were of high quality, while 20% (N = 18) were of low quality. Figure 2 shows the percentage of studies per quality level for each point on the assessment tool. Overall, studies showed higher quality in their results and discussion sections. Conversely, lower scores were found for the control of psychological and physiological variables (Figure 2). The selection of the articles for the systematic review was justified by the good quality of each study, explicitly considering the results on EFs. In general, despite many selected studies, the high quality of the studies may have reduced the risks of misinterpretation of the results.

Figure 2. Percentage of the studies and quality levels for each point of tool assessment.



	1)	2)	3)	4)	5)	6)
Low Quality (%)	5	53	3	0	0	0
Medium Quality (%)	18	40	14	17	34	16
High Quality (%)	77	7	83	83	66	84

Cross-sectional Studies

Systematic searching revealed 63 cross-sectional studies that met the inclusion criteria (see Table 3). Of these studies, twenty-nine involved adult participants (aged over 30 years), twenty examined adolescents (aged 12–22 years), two studies looked at young adults (aged 23–30 years), and twelve studies investigated the relationship between EFs and overweight/obesity in childhood (aged less than 12 years) (See Table 3). Only nine studies had a rate of males higher than females (Alarcon et al., 2016; Gentier et al., 2013; Mole et al., 2015; Pignatti et al., 2006; Qavam et al., 2014; Reyes et al., 2015; Tsai et al., 2016; Verdejo-Garcia et al., 2010; Wu et al., 2017), while Weller et al. (2008) performed two different analyses in order to examine samples of males and females independently.

All the studies adopted the BMI and the WHO classification of weight status to assign participants to different groups. For children and adolescents, the guidelines for using percentiles recommended by WHO or Centre for Disease Control and Prevention (CDC) were used (Flegal et al., 2002; Onis et al., 2007), except in two studies (Goldschmidt et al., 2018; Reyes et al., 2015) where z scores of CDC classification were considered (Harrington et al., 2013).

Studies focused mainly on differences in executive functioning between individuals with obesity and normal-weight; thirteen studies analyzed differences between participants with normal-weight and overweight; thirteen studies investigated differences in performance between participants with obesity, overweight, and normal-weight (see Table 3).

Most of the studies reported a significant difference between the groups in executive functioning, confirming the relationship between excessive body weight and executive dysfunction. Only thirteen studies reported no differences (Ariza et al., 2012; Gonzales et al., 2010; Bonger et al., 2015; Delgado-Rico et al., 2012; Frank et al., 2014; Hendrick et al., 2012; Loeber et al., 2012; Moreno-Lòpez et al., 2012; Reyes et al., 2015; Schiff et al., 2016; Sweat et al., 2017; Van der Oord et al., 2018; Voon et al., 2014).

Executive Functions in Cross-sectional Studies

Cognitive Flexibility

The tasks most adopted to assess cognitive flexibility were the Wisconsin Card Sorting Test (WCST) (Miller, 1964), the Trail Making Test (TMT, AB) (Reitan, 1958), and the Switching of Attention Task (Rogers et al., 1995) (see Table 3).

Twenty-seven studies assessed the differences between groups on cognitive flexibility (see Table 3), and only eight of them found no difference in cognitive flexibility between normal-weight and overweight/obese groups (Ariza et al., 2012; Catoira et al., 2016; Dassen et al., 2018; Delgado-Rico et al., 2012; Gonzales et al., 2010; Kittel et al., 2017; Schiff et al., 2016; Sweat et al., 2017). Generally, the results showed greater difficulty in performing tasks involving this function in participants who reported excessive body weight than normal weight. Furthermore, the study by Blanco-Gomez et al. (2015) highlighted a further difference: compared with participants with overweight, individuals with obesity showed a most severe flexibility deficit.

Inhibition

The most common cognitive tasks used to measure inhibitory control were the Stroop Color-Word Task (Stroop, 1935) and the Stop-Signal Task (Lappin & Eriksen, 1966) (see Table 3).

Forty-five studies investigated the relationship between inhibitory control and excessive body weight (see Table 3). Of these, seventeen reported no differences between the groups (Ariza et al., 2012; Bongers et al., 2015; Delgado-Rico et al., 2012; Fields et al., 2013; Gonzales et al., 2010; Hendrick et al., 2012; Loeber et al., 2012; Moreno-Lòpoez et al., 2012; Schiff et al., 2016; Stingl et al., 2012; Van der Oord et al., 2018;

Voon et al., 2014; Wu et al., 2016; Yau et al., 2014; Goldschmidt et al., 2018; Pearce et al., 2018). The other studies reported lower inhibitory control in participants affected by obesity.

Working Memory

The Digit Span Test (i.e., Backwards version) (Reynolds, 1997) and the N-Back Test (Kane et al., 2007) were used in various versions (see Table 3) to investigate differences in working memory performances.
Of the twenty-four studies that analyzed the relationship between overweight/obesity and working memory (see Table 2), six studies did not report significant differences between groups (Ariza et al., 2012; Frank et al., 2014; Gonzales et al., 2010; Pearce et al., 2018; Restivo et al., 2017; Van der Oord et al., 2018). Eighteen studies found that participants with excessive body weight performed worse than participants with normal weight on working memory tasks; moreover, obesity appeared to be associated with the poorest performances (Alarcon et al., 2016; Coppin et al., 2014).

Decision-making, Planning, and Problem-solving

The most adopted tasks for assessing decision-making, planning, and problem-solving were the Iowa Gambling Task (IGT) (Bechara et al., 2005) and the Delay Discounting Task (Richards et al., 1999) (see Table 3).
Twenty-six studies (see Table 2) investigated differences in performances between groups on tasks involving complex EFs such as decision-making, planning, and problem-solving. In all but six of them (Bongers et al., 2015; Kittel et al., 2017; Mole et al., 2015; Pearce et al., 2018; Shiff et al., 2016; Van der Ooord et al., 2018), individuals with obesity showed worse condition than normal-weight individuals in decision making, planning, and risk-taking. Furthermore, Schiff and colleagues (Schiff et al., 2016), although they did not highlight clear differences in decision-making, found that participants with obesity responded differently in terms of gratification mechanisms connected with food (as measured by the Temporal Discounting Task). In fact, they showed more sensitivity to reward stimuli. Weller et al. (2008), through the Delay Discounting task, found a tendency in women with obesity to prefer an immediate reward than a major one after some time compared to normal-weight women. This difference was not confirmed in men (Weller et al., 2008).

Table 3. Cross-sectional studies.

			Participants			Method		EF Domain		
Study	**Group**	**N**	**Age M (SD)**	**Sex (% Female)**	**BMI M (SD)**	**Cognitive Task**	**Global EF/Other EF**	**Inhibition**	**Updating**	**Cognitive Flexibility**
STUDY ON ADULT POPULATION										
Ariza et al. (2012)	OB[1] NW[2]	42 42	31.81(6.51) 29.67(6.97)	67 69	38.3(7.59) 22.07(1.97)	TMT[3] SCWT[4] WCST[5] Letter-Number Sequence	-	OB equal to NW	OB equal to NW	OB equal to NW
Bongers et al. (2015)	OB NW	185 134	35.19(7.59) 33.04(8.15)	71 74	38.18(6.17) 22.35(1.63)	Stop-Signal Task Delay Discounting Task (food cue)	OB equal to NW	OB equal to NW	-	-
Brogan et al. (2011)	OB NW	42 50	52.24(10.89) 47.34(16.34)	71 66	41.45(9.17) 24.36(3.78)	IGT[6]	OB poor than NW	-	-	-
Catoira et al. (2016)	OB NW	81 32	30 26.5	100 100	35.81 22.56	WCST TMT SCWT Verbal Fluency	-	OB poor than NW	-	OB equal to NW
Cohen et al. (2011)	OW NW	42 107	58.9(8.3) 61.2(8.0)	48 52	31.8(6.8) 24.1(1.4)	SCWT WCST TMT Digit Span	-	OB poor than NW	OB poor than NW	OB poor than NW
Danner et al. (2012)	OB OB-BED[7] NW	18 19 30	44.56(13.36) 38.05(10.97) 36.13(14.09)	100 100 100	30.84(3) 28.74(6.25) 22.32(1.96)	IGT	OB poor than NW	-	-	-
Dassen et al. (2018)	OB NW	82 71	41.12(12.62) 43.40(13.44)	64.4 77.5	38.94(5.24) 22.63(1.53)	2-Back Task Stop-Signal Task TMT	-	OB poor than NW	OB poor than NW	OB equal to NW
Deckers et al. (2017)	OB NW	545 1262	58(15) 48.9(16.2)	58 46	31.2(3.9) 24.9(2.5)	Concept Shifting Test	-	-	-	OB poor than NW
Demos et al. (2017)	OB NW	37 30	46.95(7.9) 43.97(8.9)	100 100	33.5(3.9) 22.7(1.8)	Food Choice Decision Making Task	OB poor than NW	-	-	-
Fagundo et al. (2012)	OB AN[8] NW	52 35 137	40.5(11.1) 28.1(8.2) 24.8(7)	100 100 100	39.8(7.4) 17.2(1.4) 21.5(2.7)	WCST SCWT IGT	OB poor than NW	OB poor than NW	-	OB poor than NW

Frank et al. (2014)	OB ExOB[9] NW	11 9 11	42.6(4) 42(2.8) 36.6(3.8)	100 100 100	40.2(0.8) 27.1(0.9) 21.4(0.5)	Working Memory Task (food cue)	-	-	OB equal to NW	-
Galioto et al. (2013)	OB OW[10] NW	81 210 288	51.78(16.96) 50(17.24) 44.72(18.37)	55.9 37.5 58	34.67(5.59) 27.12(1.45) 22.35(1.73)	Digit Span Maze Test Switching of Attention Task	OB poor than NW	-	OB poor than NW	OB poor than NW
Gameiro et al. (2017)	OB NW	76 38	43.24(9.05) 40.53(10.75)	68 71	>30 <25	WCST Go/No-Go Task Colour Trait Test Verbal Fluency Motor Series	-	OB poor than NW	-	OB poor than NW
Gonzales et al. (2010)	OB OW NW	12 11 9	48.5(8.6) 52(5.1) 51.8(4.3)	50 45 77	34.4(3.5) 27.4(1.4) 22.4(2.2)	Digit Span COWAT[11] TMT n-Back Task	-	OB equal to OW equal to NW	OB equal to OW equal to NW	OB equal to OW equal to NW
Gunstad et al. (2007) [1]	OW NW	140 178	32.40(9.10) 31.56(8.71)	46.4 55.1	28.4(4.42) 22.09(1.71)	Verbal Interference Task Switching of Attention Task Maze Test	OB poor than NW	OB poor than NW	-	OB poor than NW
Gunstad et al. (2007) [2]	OW NW	58 32	60.4(7.62) 58.34(6.62)	55.1 53.4	29.17(3.54) 23.09(1.59)	Verbal Interference Task Switching of Attention Task Maze Task	OB poor than NW	OB poor than NW	-	OB poor than NW
Hendrick et al. (2012)	OB OW NW	13 12 18	34.8(9.6) 33.2(16.7) 26.2(6.7)	100 100 100	33.2(2.6) 25.6(2) 20.2(1)	Stop-Signal Task	-	OB equal to OW equal to NW	-	-
Lasselin et al. (2016)	OB-LowCR[12] OB-HighCR[13] NW	29 37 20	39.4(10.5) 37.9(9) 38.9(10.1)	62 89 90	40.7(3.7) 42(3.8) 22(3)	IED[14]	-	-	-	OB-HighCR poor than OB-LowCR; NW
Loeber et al. (2012)	OB NW	20 20	47.9(12.5) 44.9(11.7)	65 60	38.8(6.3) 22.6(1.1)	Go/No-Go Task [food cue] Dot Probe Task (food cue)	-	OB equal to NW	-	-

Mole et al. (2015)	OB NW	30 30	44.06(9.7) 43.59(10.01)	37 37	32,72(3.41) 24.11(2.89)	Delay Discounting Task Stop-Signal Task Information Sampling Task	OB poor than NW	OB equal to NW	-	-
Navas et al. (2016)	OB OW NW	20 21 38	32.15(5.96) 35(6.31) 33.18(6.59)	55 52 58	35.5(2.6) 27.34(1.59) 22.21(1.70)	The Ehel of Fortune Task IGT	OB poor than OW; NW			
Perpina et al. (2017)	OB NW	27 39	47.78(11.46) 31.9(13.54)	85.2 76.9	43.92(10.04) 23.21(3.48)	WCST IGT	OB poor than NW	-	-	OB poor than NW
Pignatti et al. (2006)	OB NW	34 20	43.40(8.13) 46.65(16.33)	42 50	42.17(6) 22.16(1.83)	IGT	OB poor than NW	-	-	-
Restivo et al. (2017)	OB-Bar[15] OB-BarDDM[16] NW	25 21 20	43.9(10.7) 43.2(10.9) 43.8(11)	92 90 90	44.7(2.9) 43.7(4.8) 22.4(2)	COWAT SCWT WCST Colour Trail Test PASAT[17]	-	OB-Bar; OB-BarDDM poor than NW	OB-Bar; OB-BarDDM poor than NW	OB-Bar; OB-BarDDM poor than NW
Schiff et al. (2016)	OB NW	23 23	36.2(9.5) 33.8(8.9)	78 78	36.2(5.7) 22.4(2.2)	Temporal Discounting Task TMT FAB[18] Simple RT Task Choice RT Task Sterburg Task Simon Task	OB equal to NW	OB equal to NW	OB equal to NW	OB equal to NW
Spitoni et al. (2017)	OB NW	24 37	49.8(13.66) 35.7(11.2)	79 65	41.1(8.03) 22.5(3.01)	BADS[19]-Rule shift Cards Hayling Sentence Completion Task	-	OB poor than NW	-	-
Stanek et al. (2013)	OB NW	152 580	43.45(11.28) 47,66(18)	84 55	45.23(6.91) 25.84(4.97)	Digit Span Switching of Attention Task Verbal Interferences Maze Test	OB poor than NW	OB poor than NW	OB poor than NW	OB poor than NW

Stingl et al. (2012)	OB NW	34 34	36.5(9.5) 38.4(11)	70 70	30.4(3.2) 22(2.1)	N-Back Visual Task (food cue)	-	-	OB poor than NW	-
Van der Oord et al. (2018)	OB NW	39 25	42.82(13.23) 44.9(15.32)	82.1 72	39.7(5.31) 22.94(1.43)	Stop-Signal Task IGT Chessboard Working Memory Task	OB equal to NW	OW equal to NW	OW equal to NW	-
Voon et al. (2014)	OB NW	30 30	42.97(8.59) 43.59(10.01)	-	32.72(3.41) 24.11(2.89)	Premature Responding Task	-	OB equal to NW	-	-
STUDY ON ADOLESCENTS										
Alarcon et al. (2016)	OB OW NW	18 46 88	14.4(0.4) 13.8(0.2) 14.2(0.1)	33 46 45	%Score 96.9(0.3) 90(0.4) 58.9(1.8)	WS-WM[20]	-	-	OB poor than OW; NW	-
Bauer & Manning (2016)	OW NW	74 84	15.59(1.30) 15.57(1.24)	100 100	%Score >85° <85°	Visual Working Memory Task	-	-	OW poor than NW	-
Calvo et al. (2014)	OB NW	30 32	21.21(2.45) 21.06(2.32)	60 53.1	36.36(6.17) 21.66(1.78)	Go/No-Go Task Running Memory Continuous Performance Task Standard Continuous Performance Task	-	OB poor than NW	OB poor than NW	-
Delgado-Rico et al. (2012)	OW NW	42 21	14.19(1.38) 14.14(1.46)	67 48	29.15(4.51) 19.84(2.64)	SCWT (Stroop-Switching Performance)	-	OW equal to NW	-	OW equal to NW
Field et l. (2013)	OB OW NW	21 20 20	14.86(0.85) 15.2(0.67) 15(0.86)	52 55 60	>95° 85°- 95° 5°- 85°	Delay Discounting Task Go/No-Go Task Conner's Continuous Performance Test	OB; OW poor than NW	OB equal to OW equal to NW	-	-
Galioto et al. (2014)	OB NW	36 36	21.2(2.9) 20.7(2)	61.1 50	36.4(5.7) 22(1.7)	Go/No-Go Task Running Memory Continuous Performance Task	-	OB poor than NW	OB poor than NW	-

Kittel et al. (2017)	OB OB-Bed NW	22 22 22	14.82(2.63) 14.91(2.22) 15.23(2.39)	82 82 82	%score 98.91(2.3) 99.16(0.57) 58.91(24.03)	IGT SCWT	OB equal to OB-Bed equal to NW	OB; OB-Bed poor than NW	-	OB equal to OB-Bed equal to NW
Maayan et al. (2011)	OB NW	54 37	17.5(1.59) 17.32(1.59)	63.6 56.8	39.86(9.46) 21.67(2.49)	SCWT TMT COWAT WRAML-WM[21]	-	OB poor than NW	OB poor than NW	OB poor than NW
Moreno Lopez et al. (2012)	OW NW	36 16	14.22(1.4) 14.13(.136)	72 56	28.53(4.97) 20.26(2.8)	SCWT	-	OB equal to NW	-	-
Nederkoorn et al. (2006)	OB-Bed OB-NBed NW	15 15 31	13.7 13.9 13.7	67 60 61	33(4.3) 33.5(4.4) 19.3(2.0)	Stop-Signal Task Door Opening Task	OB poor than NW	OB poor than NW	-	-
Qavam et al. (2015)	OB OW NW	40 40 40	[15-18]	0 0 0	%Score >95° 85°-95° 5°-85°	TOL[22]	OB poor than OW; NW. OW poor than NW	-	-	-
Sellaro & Colzato (2017) [1]	OW NW	17 22	23.4(0.8) 21.2(0.6)	75 77	27.7(0.6) 21.9(0.4)	Stop-Signal Task	-	OW poor than NW	-	-
Sellaro & Colzato (2017) [2]	OW NW	19 24	22.9(1) 20.5(0.5)	58 79	28.7(0.6) 21.7(0.4)	Simon Task	-	OW poor than NW	-	-
Steenbergen & Colzato (2017)	OW NW	26 26	20.27(0.44) 20.36(0.41)	73 81	27.58(0.41) 21.67(0.25)	Switching of Attention Task	-	-	-	OW poor than NW
Sweat et al. (2017)	OB NW	108 54	19.6(1.54) 19.39(1.52)	63 53.7	35.57(4.97) 21.45(1.87)	SWCT TMT TOL	-	OB equal to NW	-	OB equal to NW
Vantieghem et al. (2018)	OB NW	62 30	15.8(1.8) 16(1.1)	71 47	39.9(8.19) 20.95(2.11)	SCWT	-	OB poor than NW	-	-
Verbeken et al. (2014)	OW NW	64 66	13.59(1.62) 12.42(1.16)	54.2	Adjusted BMI (%) 145.37(16.27) 102.56(8.99)	HDT[23]	OW poor than NW	-	-	-
Verdejo-Garcia et al. (2010)	OW NW	27 34	14.3(1.2) 15.29(0.91)	41 38	31.58(7.08) 21.01(1.97)	SCWT Five-Digit Test TMT IGT	OW poor than NW	OW poor than NW	-	OW poor than NW

Weller et al. (2008) [1]	OB NW	29 26	19.6(2.9) 20(2.6)	100 100	38.4(6.6) 21.9(2.3)	Delay Discounting Task	OB poor than NW	-	-	-
Weller et al. (2008) [2]	OB NW	19 21	19.2(1.3) 19.4(1.5)	0 0	35.4(4.8) 22.3(1.2)	Delay Discounting Task	OB equal to NW	-	-	-
Wu et al. (2016)	OB NW	19 20	21.3(2.6)	74 70	33(2.9) 22.2(2.2)	SCWT TMT Verbal Fluency Digit Span	-	OB equal to NW	OB poor than NW	OB poor than NW
Yau et al. (2014)	OB NW	30 30	17.64(1.62) 17.22(1.55)	57 63	35.47(5.88) 21.12(2.18)	TMT WCST SCWT COWAT	-	OB equal to NW	OB poor than NW	OB poor than NW
STUDY ON YOUNG ADULTS										
Coppin et al. (2014)	OB OW NW	17 16 16	25.17(4.39) 24.94(4.55) 24.25(4.25)	53 44 56	36.02(6.54) 27.63(1.49) 22.43(1.45)	CCPT[24]	-	-	OB, OW poor than NW	-
Pooja et al. (2014)	UW NW NW2 OW OB	39 50 58 58 25	26.9 [20-42]	100	<18.5 18.5-22.9 23-24.9 25-29.9 30	Digit Symbol Test SCWT Ascending Digit Task	-	OB poor than NW	OB poor than NW	OB poor than NW
STUDY ON CHILDS										
Blanco-Gomez et al. (2015)	OB OW NW	39 149 316	[6-10]	49 53 50	%Score >97 95-97 <95	Children's Colour Traits Test (1,2) Five Digit Test	-	OB poor than OW; NW	-	OB poor than OW; NW
Bozkurt et al. (2017)	OB NW	92 55	11.85(2.43) 11.9(2.96)	56 54	29.73(2.33) 21.07(1.81)	FTT[25] SDC[26] SCWT SAT[27] CPT[28]	OB poor than NW	OB poor than NW	OB poor than NW	OB poor than NW
Gentier et al. (2013)	OB NW	19 19	9.8(1.5) 9.9(1.5)	47 47	Cut-off (Cole et al. 2000) 21.62(3.51) 16.48(1.76)	Four Choice Reaction Time Task	OB poor than NW	-	-	-

Goldschmidt et al. (2018)	OW-LC[29] OW-C[30] NW-C[31]	26 34 15	10.2(0.9) 10.8(1.1) 10.4(1.1)	61 56 60	z-score 2.08(0.47) 2.02(0.47)	Flanker Task DCCST[32] IGT TOL List Sorting	OB-LC; OB-C poor than NW-C	OB-LC equal to OB-C equal to NW-C	OB-LC; OB-C poor than NW-C	-
Kamijo et al. (2012) a)	OB OW NW	30 26 70	9(0.5) 8.7(0.6) 8.9(0.6)	100 100 100	%score >95° >85° >5°	Go/No-Go Task	-	OB poor than NW	-	-
Kamijo et al. (2012) b)	OB NW	37 37	9(0.5) 8.9(0.5)	51 51	%score >95° 5°-85°	Go/No-Go Task	-	OB poor than NW	-	-
Kamijo et al. (2012) c)	OB NW	37 37	8.9(0.6) 8.8(0.6)	54 54	%score 98(1.4) 56.8(19.9)	Flanker Task	-	OB poor than NW	-	-
Pearce et al. (2018) [1]	OB NW	41 37	13.3(3.4) 13.1(2.7)	54 30	%Score 98.8(1.2) 58.3(26.1)	BART[33]	OB equal to NW	-	-	-
Pearce et al. (2018) [2]	OB NW	29 30	11.4(2.6) 11.9(2.6)	48 40	%Score 98.5(1.3) 60.7(25.4)	Stop-Signal Task N-Back Task	-	OB equal to NW	OB equal to NW	-
Reyes et al. (2015)	OW NW	93 92	10.2(1) 10.3(0.2)	44 46	z-score 1.9(0.6) 0.1(0.5)	SCWT Go/No-Go Task		WB poor than NW		
Skoranski et al. (2013)	OB NW	28 32	12.8(2.4) 12.8(2.5)	79 47	%Score >85° 5°- 85°	Arrow Task		OB poor than NW		
Tsai et al. (2016)	OB NW	26 26	(month) 114.58(3.69) 113.73(3.85)	31 31	%Score >95° 5°-85°	Posner Paradigm Task		OB poor than NW		
Wu et al. (2017)	OB NW OW	44 23 92	12.38(1.22) 11.78(1) 11.93(0.92)	32 26 56	>30 25-30 <25	Digit Span Memory Task (digits; digit-food cue; digit-cartoon)	-	-	OW poor than NW	-

1OB: Obese. 2NW: Normal Weight. 3TMT: Trail Making Test. 4SCWT: Stroop Colour-Word Task. 5WCST: Wisconsin Card Sorting Test. 6 IGT: Iowa Gambling Task.7OB-BED: Obese with Binge Eating Disorder. 8AN: Anorexia Nervosa. 9ExOB: Normal weight people who were obese. 10OW: Overweight. 11COWAT: Controlled Oral Word Association Task. 12OB-LowCR: Obese with low sensitivity to C-reactive protein.13OB-HighCR: Obese with high sensitivity to C-reactive protein.14IED: Intra/Extra-dimensional set shift test. 15OB-Bar: Obese and on the waiting list for bariatric intervention. 16OB-BarDDM: Obese and on the waiting list for bariatric intervention with Major Depressive Disorder. 17PASAT: Paced Auditory Serial Attention Test. 18FAB: Frontal Assessment Battery.19 BADS: Behavioural Assessment of the Dysexecutive Syndrome. 20WS-WM: Working Memory Task of Wechsler Scale. 21WRAML-WM: Wide-Range Assessment of Memory and Learning-Working Memory. 22TOL: Tower of London. 23HDT: Hungry Donkey Task. 24CCPT: Conditioned Cue Preference Test. 25FTT: Finger-Tapping Test. 26SDC: Symbol Digit Coding. 27SAT: Shifting Attention Test. 28CPT: Continuous Performance Test. 29OW-LC: Overweight with high loss of control. 30OW-C: Overweight with low loss of control. 31NW-C: Normal weight with low loss of control. 32DCCST: Dimensional Change Card Sort task. 33BART: Balloon Analogue Risk Task.

Discussion Cross-Sectional Studies

The analysis of the cross-sectional studies confirmed the existence of a relationship between excessive body weight and executive functions, even if it did not indicate the direction of this relationship. Many cognitive tasks were adopted to assess executive functioning, but the results remained consistent, despite their heterogeneity. Although the inhibition appears to be the most analyzed EF related to excessive body weight, the very different demands of the tasks did not determine whether one single EF is more closely involved than the others in the relationship with overweight/obesity. The studies that failed to confirm a relationship between EFs and overweight/obesity were characterized by small sample sizes (Hendrick et al., 2012; Schiff et al., 2016) or a high number of cognitive tasks (Gonzales et al., 2010).

The present systematic review included studies that consider people of different ages, covering the lifespan from childhood to old age. This choice aimed to investigate whether the relationship between EFs and overweight/obesity presents similar characteristics, regardless of the participants' age. The results of the review confirmed the relationship between EFs and overweight both in studies examining adults and young adults (Gunstad et al., 2007; Fagundo et al., 2012; Coppin et al., 2014) and in those that looked at children (Yadava and Sharma, 2014; Bozkurt et al., 2017) and adolescents (Nederkoorn et al., 2006; Galioto Wiedemann et al., 2014). These results prevent us from making inferences about the causality of this relationship over the lifespan but highlight the existence of a negative relationship between executive performances and excessive body weight, regardless of the age considered.

Many studies tried to control for certain variables (gender, age, and education) that might influence executive performances by matching samples, controlling for these variables through statistical analysis, or including them as moderators of the relation (Deckers et al., 2017; Gunstad et al., 2007; Kittel et al., 2017; Perpina et al., 2017). This methodological aspect highlighted some dimensions (e.g., demographical variables as gender or educational level) that might influence the relation between body weight and EFs; therefore, considering these variables can further strengthen the results (Kittel et al., 2017).

Generally, the studies used suitable inclusion criteria that exclude individuals with chronic medical conditions, psychopathologies, or eating disorders to avoid an effect of these dimensions on the results (Fagundo et al., 2012; Galioto et al., 2013; Galioto Wiedemann et al., 2014). Moreover, in some studies, physiological differences between participants with normal-weight and overweight/obesity were reported. Participants with severe obesity showed worse blood pressure, cholesterol levels, insulin resistance (Maayan et al., 2011; Perpiñá et al., 2017), and levels of glycolic metabolism activation although, in the absence of pathological medical conditions in line with previous results (Heymsfield and Wadden, 2017).

Both psychopathological and physiological aspects related to obesity, and severe obesity, impact on the executive functioning. Therefore, these variables should be controlled in further studies. Although the cross-sectional studies showed no clear direction in the overweight–executive functioning relationship, many authors advanced various hypotheses (Gonzales et al., 2010; Galioto Wiedemann et al., 2014). For example, Kamijo et al. (2012a) hypothesized that ineffective inhibitory control of the prefrontal cortex would cause excessive consumption of calories directly associated with increased body fat. Moreover, other authors also considered the dopaminergic mechanism involved in executive processing and weight variations (Arnsten and Li, 2005). Neuroimaging studies of individuals with obesity have shown an association between the hypoactivation of dopaminergic D2-receptors and a decrease in neural metabolism in the areas most involved in executive functioning (Volkow et al., 2011). Furthermore, dopamine is also implicated in the reward system (Volkow et al., 2011; Smith and Robbins, 2013). This neural system resulted impaired in individuals with excessive body weight, and these alterations could influence the approach toward food in terms of consumption of hypercaloric ones to achieve higher gratification (Schiff et al., 2016). All these findings could support theoretical models on the genesis of obesity (Davis et al., 2007b; Smith and Robbins, 2013) that view changes in executive functioning as one of the leading causes of weight gain. The hypothesis of executive dysfunctions as a cause of inappropriate eating behavior could partially support the theoretical model of Food Addiction (Wang et al., 2004; Smith and Robbins, 2013).

Other authors viewed executive deficits as a consequence of obesity, recognizing it as a cause of neurophysiological and metabolic diseases, such as changes in insulin sensitivity (Gonzales et al., 2010), inflammatory processes as a result of body fat accumulation (Lasselin et al., 2016), and changes in cerebrovascular blood flow (Verdejo-García et al., 2010; Qavam et al., 2015). These alterations could be the cause of structural (e.g., a reduction of the orbitofrontal cortex) (Cohen et al., 2011) or functional (e.g., reduced functional connectivity of executive networks) (Tsai et al., 2016) changes in the cerebral areas involved in executive functioning. This vision seems to be in line with the Neuroinflammation Model (Perry, 2004), assuming that high BMI is associated with a systemic inflammation that negatively affects cognitive functions, including executive ones (C-reactive protein and interleukin would play an essential role in this process; Bourassa and Sbarra, 2017). It also agrees with the model proposed by Sellbom and Gunstad (2012), in which the changes in blood flow and metabolism of the frontal lobes as well as the atrophy of the frontal and temporal lobes would cause impairment in inhibitory control, increasing the overeating behaviors (Sellbom and Gunstad, 2012).

Interestingly, the consistent results of the review confirm that even a moderate increase in body weight may be associated with a decrease in executive performances (Verdejo-García et al., 2010; Cohen et al., 2011; Sellaro and Colzato, 2017). These views are supported by results obtained comparing groups of participants with normal-weight, overweight, and obesity, in which differences in performances also emerged between overweight and obesity conditions (Galioto Wiedemann et al., 2014; Wu et al., 2017).

Another aspect highlighted by the cross-sectional studies is the role of certain psychological variables related to BMI (Catoira et al., 2016; Restivo et al., 2017) that appear to modulate the relationship between EFs and excessive body weight. The presence of high levels of anxiety and depression in individuals with obesity, even in the absence of established psychopathologies, appears to result in worse executive performances (Restivo et al., 2017). These findings could be linked to the theoretical model of Emotionally Driven Eating (Dallman, 2010), which postulated that overeating, related to overweight, is a dysfunctional attempt to regulate emotions in people characterized by a deficit in emotion regulation.

Longitudinal Studies

Our systematic search allows selecting twenty-eight longitudinal studies investigating executive functioning in overweight or obese individuals (see Table 4). Of these, eighteen examined adult participants (aged more than 30 years), five looked at children (aged less than 12 years), and five involved adolescents (aged 12-22 years) (See Table 4).

All studies used the BMI to classify overweight and obesity, although z-scores (Augustijn et al., 2018; Davis et al., 2007; Davis et al., 2011), percentiles (Pauli-Pott et al., 2010), or adapted BMI scores (Verbeken et al., 2014) were used in studies involving children.

Five studies (Alosco et al., 2014; Kulendran et al., 2017; Stinson et al., 2018; Xie et al., 2017; Xu et al., 2018) reported a higher percentage of females than males in their sample. Twelve studies (Bryan and Tiggemann, 2001; Davis et al., 2007a, 2011; Pauli-Pott et al., 2010; Witbracht et al., 2012; Kulendran et al., 2014; Galioto et al., 2016; Demos et al., 2017; Xie et al., 2017; Xu et al., 2017; Augustijn et al., 2018; Vantieghem et al., 2018) analyzed the effects of non-invasive programs aimed at weight-loss: some interventions integrated various modalities of treatment, specifically diet and physical activity (Pauli-Pott et al., 2010; Kulendran et al., 2014; Galioto et al., 2016; Demos et al., 2017; Xie et al., 2017; Xu et al., 2017; Vantieghem et al., 2018); while others focused only on diet programs (Bryan and Tiggemann, 2001; Witbracht et al., 2012) or physical activity (Davis et al., 2007a, 2011). Furthermore, two studies (Kulendran et al., 2014; Augustijn et al., 2018) provided residential interventions, with treatment lasting from four (Davis et al., 2011) to fifty-two weeks (Pauli-Pott et al., 2010). At least two measurements were taken in all the studies: one before and one after the procedure. Ten studies examined the effects of bariatric surgery on the executive functioning in participants with severe obesity (Spitznagel et al., 2013, 2014; Alosco et al., 2014a,c,d, 2015; Galioto et al., 2015; Kulendran et al., 2017; Pearce et al., 2017). The analysis of EFs was performed before surgery and at follow-up, with time intervals ranging from 12 weeks (Spitznagel et al., 2013, 2014) to 48 months (Alosco et al., 2014d). In some cases, more than one follow-up was carried out (Spitznagel et al., 2013, 2014; Alosco et al., 2014d).

All the studies investigating weight reduction in participants with obesity reported a general improvement in EFs performances. Only Pearce et al. (2017) failed to detect any significant changes. Four studies assessed the effects of cognitive interventions on EFs in obese participants showing a general improvement in executive performances associated with a reduction in body weight. Specifically, two studies evaluated the benefits of Cognitive Remediation Therapy (Alosco et al., 2014b; Allom et al., 2018), one assessed the impact of an intervention focused on Working Memory (Galioto et al., 2015), and one centered on the effects of a treatment aimed at strengthening cognitive functions in general (Verbeken et al., 2014).

Two studies analyzed the trend over time of body weight and executive functioning in adults with obesity (Deckers et al., 2017; Stinson et al., 2018), reporting inconsistent results. Deckers et al. (2017) did not find any relationship between weight changes and executive performance, while Stinson et al. (2018) found evidence of the role of EFs, specifically of reduced inhibitory control, in maintaining the excessive body weight.

Eleven studies (Pauli-Pott et al., 2010; Spitznagel et al., 2013, 2014; Kulendran et al., 2014; Galioto et al., 2015, 2016; Xu et al., 2017; Augustijn et al., 2018; Dassen et al., 2018a; Stinson et al., 2018) investigated the predictive role of the executive performances on body weight changes, observing that appropriate executive functioning predicted a reduction in body weight in participants with obesity or overweight.

Executive Functions in Longitudinal Studies

Cognitive Flexibility

The tasks most adopted to assess cognitive flexibility were the WCST, TMT, and Switching of Attention Task (see Table 4). Of the eleven studies that investigated the relationship between cognitive flexibility and obesity (see Table 4), six studies (Bryan and Tiggemann, 2001; Alosco et al., 2014c; Spitznagel et al., 2014; Deckers et al., 2017; Augustijn et al., 2018; Stinson et al., 2018) failed to confirm this relationship. Those who found an association between obesity and executive functioning reported improved performance due to weight reduction.

Furthermore, negative performance appeared to be associated with less weight reduction over time (Spitznagel et al., 2013; Augustijn et al., 2018).

Inhibition

The Stroop Color-Word Task and Stop-Signal Task were used to investigate cognitive and motor inhibition (see Table 4). Thirteen studies reported a relationship between BMI and cognitive inhibition (Bryan and Tiggemann, 2001; Pauli-Pott et al., 2010; Alosco et al., 2014d, 2015; Kulendran et al., 2014, 2017; Galioto et al., 2015, 2016; Xie et al., 2017; Xu et al., 2017; Augustijn et al., 2018; Stinson et al., 2018; Vantieghem et al., 2018). Some studies showed that inhibition control predicts the reduction of body weight considering both bariatric surgery (Kulendran et al., 2017) and weight loss programs (Pauli-Pott et al., 2010; Kulendran et al., 2014; Galioto et al., 2016; Xu et al., 2017; Augustijn et al., 2018; Stinson et al., 2018). Other studies showed an improvement in the inhibition after bariatric surgery (Alosco et al., 2014d, 2015; Galioto et al., 2015) or weight-loss programs (Bryan and Tiggemann, 2001; Xie et al., 2017; Vantieghem et al., 2018).

Working Memory

The task most often used to investigate working memory was the Digit Span Test (Reynolds, 1997) (see Table 4). Eight studies reported a negative relationship between working memory and body weight (Spitznagel et al., 2013, 2014; Alosco et al., 2014b,d, 2015; Galioto et al., 2015; Augustijn et al., 2018; Dassen et al., 2018b). Indeed some authors found an improvement of the performance in working memory tasks after bariatric surgery (Alosco et al., 2014b,d, 2015; Galioto et al., 2015), while other authors found a predictive role of working memory performance in the outcome of weight reduction programs (Augustijn et al., 2018; Dassen et al., 2018b) or bariatric surgery (Spitznagel et al., 2013, 2014);

better performance predicted the success of interventions. Conversely, three studies found no relationship between obesity and working memory (Bryan and Tiggemann, 2001; Galioto et al., 2016; Pearce et al., 2017).

Decision-making

Decision-making, as measured with the Iowa Gambling Task, did not appear to be directly associated with weight reduction in patients with obesity and overweight (Witbracht et al., 2012; Stinson et al., 2018). Only Demos et al. (2017) observed an improvement in decision-making following a reduction in body weight, but these authors used a task that included food-related stimuli.

Table 4. Longitudinal Studies.

	Participants					Method			EF Domain			
Study	**Group**	**N**	**Age M (SD)**	**Sex (% Female)[a]**	**BMI[b] M (SD)**	**Treatment**	**Cognitive Task**	**Program/Follow-Up**	**Global EF/Other EF**	**Inhibition**	**Updating**	**Cognitive Flexibility**
* *Allom et al. (2018)*	OB-CRT[1] OB-C[2]	42 38	41.39(7.85)	86	39.76(7.53)	*Cognitive Remediation Therapy*	WCST[3] TMT[4]	3 months	OB-CRT ↑ OB-C =	-	.	OB-CRT ↑ OB-C =
Alosco et al. (2014a)	OB-AD[5] OB-NAD[6]	14 80	40(11.42) 45.1(10.99)	21.4 15	T1.45.17(5.02) T2.37.85(5.43) T1.46.07(5.33) T2.38.06(4.86)	*Bariatric Surgery [Alzheimer History]*	TMT Maze Task	12 weeks	OB-AD= OB-NAD=	-	.	OB-AD= OB-NAD=
Alosco et al. (2014b)	OB-Bar[7] OB-C	63 23	42.29(11.42) 41.13(12.55)	90.5 95.7	T1.46.5(5.26) T2.31.34(6.42) T1.40.9(5.24) T2.40.9(5.64)	*Bariatric Surgery*	Digit Span Switching Attention Task Maze Task	24 months	OB-Bar ↑ OB-C =	-	OB-Bar ↑ OB-C =	OB-Bar ↑ OB-C =
Alosco et al. (2014c)	OB-Bar	78	43.5(10.59)	82.1	T1.46.63(5.28) T2.30.51(5.39)	*Bariatric Surgery*	Switching of Attention Task Maze Task	12 months	OB-Bar ↑	-	-	OB-Bar ↑
Alosco et al. (2014d)	OB-Bar	50	44.08(10.76)	92	T1.46.61(5.27) T2.32.35(6.57) T3.33.02(6.27)	*Bariatric Surgery*	Digit Span Switching of Attention Task Verbal Interference Maze Task	I. 36 months II. 48 months (LD)[8]	I.OB-Bar ↑ II. OB-Bar ↑	I.OB-Bar ↑ II. OB-Bar ↑	I.OB-Bar ↑ II. OB-Bar ↑	I.OB-Bar ↑ II. OB-Bar ↑

Alosco et al. (2015)	OB-Bar	84	43.86(10.39)	83.3	T1.46.88(6.08) T2.30.05(5.39)	*Bariatric Surgery*	Digit Span Switching of Attention Task Verbal Interference Task	12 months	-	OB-Bar ↑	OB-Bar ↑	OB-Bar ↑
**Augustijn et al. (2018)*	OB	T1.32 T2.30	9.6(1.1)	T1.56 T2.60	Z scores T1. 2.7(0.3) T2.2.0(0.4)	*Weight Loss Program*	CANTAB[9]	6-10 months	OW↑	OW↑	OW↑	OW=
Bryan & Tiggerman (2001)	OB-WL[10] OB-C	42 21	48.9(8.2) 50.9(7.3)	100 100	T1.34.1(4.3) T1.35.2(4.8)	*Weight Loss Program*	TMT WCST Self-Ordered Piniting Task Initial Letter Fluency Excluded Letter Fluency Digit Span	12 weeks	-	OB-WL ↑ OB-C=	OB-WL = OB-C=	OB-WL = OB-C=
**Dassen et al. (2018)*	OW-WMT[11] OW-C	T1.51 T2.34 T1.40 T2.36	47.97(10.69)	74.7	T1.30.96(3.64) T2.29.95(3.46) T1.30.49(3.97) T2.30.17(4.14)	*Working Memory Training*	2-Back Task	25 session	-	-	OW-WMT↑	-
Davis et al. (2007)	OW-HE[12] OW-LE[13] OW-NE[14]	32 33 29	9.2(0.84)	60	z-score 2.1(0.4)	*Weight Loss Program: Aerobic Exercise*	CAS[15]: Planning Subscales for EF	15 weeks	OW-HE↑	-	-	-
Davis et al. (2011)	OW-HE	56 55 60	9.3(1.0)	56	z-score 2.1(0.4)	*Weight Loss Program: Aerobic exercise*	CAS: Planning Subscales for EF	13 weeks	OW-HE↑	-	-	-

	OW-LE OW-NE											
Deckers et al. (2017)	OB NW	T1.545 T2.190 T1.1262 T2.834	T1.58(15) T2.48.9(16.2) T1.48.9(16.2) T2.46.7(14.9)	I.58 II.59 I.46 II.43	T1.31.2(3.9) T2.28.7(2.4) T1.24.9(2.5) T2.24.8(2.4)	-	Concept Shifting Test	6 years 12 years	OB= NW=	-	-	OB= NW=
Demos et al. (2017)	OB-WL NW	37 30	46.95(7.9) 43.97(8.9)	100 100	T1.33.5(3.9) T1.22.7(1.8)	*Weight Loss Program*	Food Choice Decision Making Task	12-16 weeks	OB-WL↑	-	-	-
Galioto et al. (2015)	OB-Bar	72	43.55(10.21)	81.7	T1.46.32(5.51) T2.30.18(5.25)	*Bariatric Surgery*	Digit Span Switching of Attention Task Verbal Interference Verbal Fluency	12 months	OB-Bar↑	OB-Bar↑	OB-Bar↑	OB-Bar↑
**Galioto et al. (2016)*	OB	23	50.35(15.11)	68	44.21(8.82)	*Weight Loss Program*	Dot Counting Task N-Back Task Set Shifting Task Unstructured Task Flanker Task	8 weeks	-	OB↑	OB=	OB↑
**Kulendran et al. (2014)*	OB-WL	53	14.28(1.15)	60	T1.33.75(7.9)	*Weight Loss Program*	Stop-Signal Task Delay Discounting Task	2-8 weeks	-	OB-WL↑	-	-

**Kulendren et al. (2017)*	OB-Bar	45	43.42(13.06)	31	T1.44.25(6.34) T2.35.51(7.08)	*Bariatric Surgery*	Stop-Signal Task (food-cue) Temporal Discounting Task	6 months	-	OB-Bar↑	-	-
**Pauli-Pott et al. (2010)*	OW	111	11.1(2.0)	57	95° percentile	*Weight Loss Program*	Go/No-Go Task Interference Task	1 year	-	OW↑	-	-
Pearce et al. (2017)	OB-Bar OB-C NW	10 14 12	17(1.37) 16.42(1.35) 16.51(1.27)	60 71 50	T1.47.18(6.98) T1.45.32(8.19) T1.21.57(2.59)	*Bariatric Surgery*	Verbal N-Back Test Ballon analogue risk task	4 months	OB-Bar= OB-C= NW=	-	OB-Bar= OB-C= NW=	(DM area shows a reduction of activation in OB-Bar after the surgery)
Raman et al. (2018)	OB-CRT OB-C	42 38	40.6(2.4) 42.2(8.8)	86	39.2(7.4) 40.3(7.8)	*Computerised Cognitive Remediation Therapy*	WCST TMT	8 weeks 3 months	-	-	-	OB-CRT ↑ OB-C =
**Spitznagel et al. (2013)*	OB-Bar	84	44.75(9.99)	79.8	T1.46.13(5.80) T2.37.46(4.99) T3.31.07(6.44)	*Bariatric Surgery*	Switching of Attention Task Digit Span Maze Task	I.12 weeks II. 12 months	I.OB-Bar= II.OB-Bar↑	-	I.OB-Bar= II.OB-Bar↑	I.OB-Bar= II.OB-Bar↑
**Spitznagel et al. (2014)*	OB-Bar	55	45(10.28)	87.3	T1.45.11(5.11) T2.37.23(4.76) T3.31.69(5.84)	*Bariatric Surgery*	Digit Span Switching of Attention Verbal Interference Verbal Fluency Maze Task	12 weeks 36 months	OB-Bar↑	OB-Bar =	OB-Bar↑	OB-Bar =
**Stinson et al. (2018)*	OW	46	37.2(10.2)	24	28.3(6.7)	-	IGT WCST SCWT	32±25 months	OW=	OW↓	-	OW=

Vantieghem et al. (2018)	OB-WL NW	62 30	15.8(1.8) 16(1.1)	71 47	T1.39.9(8.19) T2.32.21(7.14) 20.95(2.11)	*Weight Loss Program*	SCWT	30 weeks	-	OB-WL↑	-	-
Verbaken et al. (2014)	OB-EFT[18] OB-C	22 22	11.50(1.60) 11.41(1.93)	50 41	Adjusted BMI T1. 131.58(21.70) T1. 132.91(15.98)	*Executive Function Training*	Corsi Block-Tapping Task Stop-Signal Task	Post-Test 8 weeks 12 weeks	OB-EFT ↑ OB-C=	-	-	-
Witbracht et al. (2012)	OB	29	32.7(9.2)	100	32(2.6)	*Weight Loss Program*	IGT	12 weeks	OB↑	-	-	-
Xie et al. (2017)	OB-WL OB-C	30 28	15.07(0.83) 15.18(0.39)	27 36	T1.32.83(3.84) T2.29.19(3.52) T1.30.90(1.95) T2.30.47(2.13)	*Weight Loss Program*	Flanker Task	4 weeks	-	OB-WL↑ OB-C=	-	-
**Xu et al. (2017)*	OB-WL	31	18,2(3,2)	39	34,4(4,8)	*Weight Loss Program*	SCWT	4 weeks program	-	OB-WL ↑	-	-

Note: * EF-predicted weight loss. a. Percentage of females. b. Body Mass Index. ↑: Better performance after treatment. ↓: Worse performance after treatment. = No differences. [1]OB-CRT: Obese and in Cognitive Remediation Therapy Treatment. [2]OB-C: Obese-Control (No treatment group). [3]WCST: Wisconsin Card Sorting Test. [4]TMT: Trail Making Test. [5]OB-AD: Obese with history of Alzheimer's. [6]OB-NAD: Obese with no history of Alzheimer's. [7]OB-Bar: Obese and subjected to bariatric surgery. [8] LD: Loss Data. [9]CANTAB: Cambridge Neuropsychological Test Automated Battery. [10]OB-WL: Obese and subjected to a weight-loss programme. [11]OB-WMT: Obese and subjected to Working Memory Training. [12]OW-HE: Overweight and subjected to high-exercise training. [13]OW-LW: Overweight and subjected to low-exercise training. [14]OW-NE: Overweight with no exercise training.[15]CAS: Cognitive Assessment System. [16]SCWT: Stroop Colour-Word Task. [17]IGT: Iowa Gambling Task (for decision-making). [18]OB-EFT: Obese and subjected to Executive Function Training.

Discussion of longitudinal studies

The results of the longitudinal studies confirmed the findings reported in cross-sectional studies, highlighting a relationship between executive functioning and overweight/obesity even if the direction of this relationship remains unclear. The studies on the effects of treatments aimed at reducing body weight showed a general improvement in executive tasks. This improvement appeared to occur both in adult populations (Bryan and Tiggemann, 2001; Witbracht et al., 2012) and in children and adolescents (Davis et al., 2011; Kulendran et al., 2014; Vantieghem et al., 2018). Moreover, the studies focused on the ability of executive functioning to predict the success of weight-loss interventions found that higher executive functioning could be the cause of BMI reduction (see Table 4).

As for the cross-sectional studies, the authors interpreted the results based on two different types of theoretical models. One hypothesizes that excessive body weight is the cause of changes in executive functioning, according to results showing an improvement in executive tasks following treatment for weight loss (Davis et al., 2007a, 2011; Alosco et al., 2014a,b,c,d, 2015; Verbeken et al., 2014; Galioto et al., 2015; Demos et al., 2017; Xie et al., 2017; Vantieghem et al., 2018). The other theoretical view considered the EFs as predictors of eating behaviors related to excessive body weight, like overeating. Studies assessing the effects of strengthening EFs in participants with overweight or obesity (Verbeken et al., 2014; Allom et al., 2018; Dassen et al., 2018b; Raman et al., 2018) have observed both an increase in executive functioning and a reduction in BMI. This reduction may be due to improved eating behavior as a result of adequate working memory, cognitive flexibility, and inhibitory control. These enforcement functions would promote healthier behaviors, reducing the risk associated with obesity, and further improve weight reduction (Allomet al., 2018). Studies that have shown the predictive role of the EFs on the success of weight-loss treatments (Pauli-Pott et al., 2010; Spitznagel et al., 2013, 2014; Kulendran et al., 2014, 2017; Galioto et al., 2016; Xu et al., 2017; Augustijn et al., 2018) confirmed the critical role of executive functioning in the occurrence of obesity.

Concerning bariatric surgery, the effects of weight-loss on executive performances resulted only at the follow-up (Spitznagel et al., 2013; Alosco et al., 2014a; Pearce et al., 2017). On the one hand, this result may suggest that a reduction in body adiposity improve the executive functioning (Alosco et al., 2014b) as a consequence of the resolution of metabolic alterations related to excessive BMI; on the other hand, better performance at baseline could lead to an improvement in healthy eating habits (Spitznagel et al., 2013; Pearce et al., 2017), linked to a reduction of BMI over time. The results supported this last interpretation at the follow-ups that showed a higher reduction in BMI in participants with better EFs performance at baselines (Spitznagel et al., 2013; Pearce et al., 2017). Lastly, it is interesting to note that control groups with obesity that did not benefit from the treatments (Bryan and Tiggemann, 2001; Alosco et al., 2014c; Pearce et al., 2017; Xie et al., 2017) did not show improvement in performance on cognitive tasks in the follow-up assessment. Despite these findings, short-term follow-ups showed no evidence of a causal relationship of EFs on obesity, with no significant differences between participants with obesity who have reduced their body weight and those who maintained their condition unchanged (Deckers et al., 2017).

In line with these results, we can conclude that the relationship between EFs and excessive body weight appears robust even when longitudinal studies are considered. However, even considering the results of longitudinal studies appear challenging to determine the direction of this relationship, further studies are needed.

General discussion

Only in recent years, the studies focused on the relationship between excessive body weight and EFs (Fitzpatrick et al., 2013). This relationship appears to be confirmed by most of the studies, both cross-sectional (e.g., Verdejo-García et al., 2010; Cohen et al., 2011; Maayan et al., 2011; Dassen et al., 2018a) and longitudinal (e.g., Spitznagel et al., 2013; Alosco et al., 2014d, 2015; Augustijn et al., 2018), despite the heterogeneity of the tasks and the methodological framework adopted.

Functional and neuroimaging studies confirmed changes in the cortical areas involved in executive functioning in participants with obesity (Stingl et al., 2012; Alarcón et al., 2016; Tsai et al., 2016) even when cognitive tasks failed to highlight any significant differences in performance between obesity and normal-weight conditions (Hendrick et al., 2012; Frank et al., 2014; Pearce et al., 2017). The choice to select studies that considered different ages made us possible to highlight a similar pattern in the relationship between EFs and overweight/obesity in children (Blanco-Gómez et al., 2015; Tsai et al., 2016) and adults (Cohen et al., 2011; Deckers et al., 2017), despite the individual differences linked to age.

Interestingly, this systematic review allows us to observe poor performance on EFs tasks also in people with overweight, not only in those with obesity (Verdejo-García et al., 2010; Sellaro and Colzato, 2017), although only a few studies have investigated the condition of overweight (BMI between 25 and 30) compared to normal-weight (BMI lower than 25) and obesity (BMI higher than 30). These results should be explored in further studies to verify how executive functioning is expressed at the different stages of overweight and understand if the early intervention could prevent the worsening of the increase in adiposity.

As previously reported, the results of these studies have been interpreted according to two different theoretical models. In the conclusion of this systematic review, no single theoretical model appears to prevail. The empirical data can support both the one postulating the influence of executive system dysfunctions on obesity (Drewnowski, 1997; Goldstone et al., 2009; Smith and Robbins, 2013), the other viewing impairment of executive functioning as a consequence of obesity (Ricca et al., 2009; Pieper and Laugero, 2013). Other longitudinal studies are needed to clarify the relationship between obesity and executive dysfunctions. These studies could either examine the eating behavior and body weight condition of people with low executive functioning over time or monitor the executive functionality of people with overweight who become obese over time. Finally, the possibility that the relationship between executive dysfunctions and excessive body weight could be bidirectional cannot be excluded; in fact, many studies seem to suggest that bidirectionality is the real nature of this relation (Spitznagel et al., 2013; Augustijn et al., 2018; Raman et al., 2018).

An aspect of this work that should be deepened is the decision to exclude studies on preschools (younger than 5 years) and people over 70 years. Firstly, the EFs and relatives' neural areas of preschool-age children are immature and still developing (Diamond, 2013); moreover, children are still introjecting eating habits learned from the external environment (Guxens et al., 2009; Gregory et al., 2010). Accordingly, previous studies have shown a specific predictive value of EFs performance in preschool children concerning weight and eating behaviors (Park et al., 2014), and for this reason, it would be interesting to study this specific age group separately. Secondly, the studies of people over 70 years of age could be influenced by the "obesity paradox" hypothesis (Artham et al., 2008; Park et al., 2014), which recognizes the health benefits to older people in having a higher BMI. Furthermore, impairment of EFs in older people can be associated with the aging process (Fjell et al., 2016). For these reasons, although the analysis of the relationship between EFs and overweight/obesity in these two age groups could be interesting, their inclusion in the present study would have led to extreme heterogeneity.

Limitations

This systematic review was unable to identify if one specific EF had a more significant role than another on the analyzed relationship. This result could represent a limitation because it has not allowed us to establish whether differences in performance were due to changes in some functions rather than others. This limitation is due mainly to the heterogeneity of cognitive tasks (Yang et al., 2018).

Another limit could be the selection of participants from 5–70 years; in fact, also if the results are coherent, it is known that the brain continues to develop from childhood to young adulthood, and the differences related to aging could influence the relation between cognitive aspects and weight changes. These age-related differences may have covered possible results that could indicate a causal direction between the variables. Considering the longitudinal studies, the most extended follow-up period—of 4 years—was performed by Alosco et al. (2014d), though with considerable data loss. No other study investigated the relationship between EFs and body weight following body loss treatment over such a long time. This aspect represents a further limitation of the results, i.e., it is not clear whether the improvements were sustained over time or whether a subsequent reversal of the trend occurs, which might have been the reason behind the drop-out from treatment among bariatric patients. Besides, a possible change in the trend over time could indicate that it is the executive damage that influences the success of weight-loss interventions.

To not have deepened the analysis of psychological variables that could modulate the relationship between EFs and excessive body weight represents another limit. In fact, a few of the selected studies controlled the psychological dimensions, like anxiety, depression, or emotional regulation. It would be interesting to carry out an analysis of these dimensions. In fact, some studies that considered some emotional components showed that emotions could modulate the relationship between executive functioning and obesity. However, other studies did not confirm this relationship (Yau et al., 2014). Even so, examining these psychological variables might lead to a better understanding of the Emotionally Driven Eating Model (Chen et al., 2017) in individuals with no eating disorders.

Further limitations are due to the limited samples considered by both cross-sectional and longitudinal studies and the higher prevalence of females among the participants that do not allow to generalize the results. Weller et al. (2008) found different results between males and females on EF performances, and further studies would be useful to analyze gender differences.

A significant limitation of this work concerns the lack of studies comparing participants with overweight and obesity separately. This comparison would have allowed us to examine the relationship between different severities of excessive body weight and executive functioning impairment. Furthermore, a specific focus on participants with overweight would also have led to determine the cognitive characteristics that might serve as warning signs of the development of obesity.

Finally, a meta-analysis measuring the statistical power of the results obtained from the studies analyzed in this study could help better interpret the results obtained in this systematic review.

Conclusions

The analysis of the studies on the relationship between executive functioning and excessive body weight did not give us decisive responses to all the questions advanced by this systematic review but clarified a large part of the issues on this topic. A consistent relationship between executive functioning and overweight/obesity has been confirmed, but it remains unclear whether a general executive dysfunction is involved or whether one EF is more implicated than others.

Although it was not possible to confirm a specific theoretical model on the relationship between EFs and overweight/obesity, the association between these dimensions results from a complex interaction between different factors that influence both people's attitudes to food and eating and their executive functioning. Prolonged inappropriate food intake related to excessive body weight maintenance leads to poorer performance on executive tasks. Furthermore, executive impairment exacerbates inappropriate behaviors, leading to increased body fat (Stinson et al., 2018). Both these aspects are associated with a real risk of cognitive impairment in old age (Sanderlin et al., 2017) and difficulty in responding appropriately to external stimuli (Favieri et al., 2020) that is typical of executive dysfunctions and which would negatively affect the life of obese individuals. It is essential to intervene in both these dimensions to reduce the impact of obesity on quality of life.

It would be interesting in the future to evaluate the effectiveness of long-term interventions involving weight-loss programs. The success of weight-loss interventions may be strictly linked to improved executive functioning because effective executive skills would allow healthier lifestyles. In this context, it might be useful to examine the integrated model of Sellbom and Gunstad (2012) and the Emotionally Driven Eating model (Gianini et al., 2013; Wagner et al., 2013) in terms of the relationship between BMI and cognitive functioning variables such as mood and emotional regulation that were not often analyzed in the studies reviewed here.

A relevant suggestion that emerges by this review is the need for longitudinal studies that, starting from the analysis of EFs, monitor the body weight changes over time. It could be essential for structuring intervention aimed at enhancing EFs to prevent the drop-out rate among patients with severe obesity who fail to benefit for a long time from the effects of treatments (Galioto et al., 2016; Xu et al., 2017), by favoring the long-term maintenance of the lower weight achieved. It needs to reduce the risk of further weight gain in people with overweight, thereby preventing severe obesity. Moreover, an integrated approach that also takes emotion regulation and mood into account could be the best strategy for countering dysfunctional eating behaviors and executive functioning; therefore, it would be necessary to develop an integrated theoretical model that should jointly consider EFs, eating behavior, emotion regulation, and mood in the field of overweight and obesity.

CHAPTER 2. Executive Functions and Overweight: the role of Food Stimuli.

Introduction

In eating behavior research, the recent studies agree in considering executive functions as moderators in the relationship between intention and execution of eating (Nederkoorn et al., 2010; van Elburg & Treasure, 2013), influencing the approach to food choices. Executive functions (EFs) included a set of cognitive processes that control and drive thoughts and goal-directed behaviors (e.g., cognitive inhibition, working memory, shifting, Miyake et al., 2000; Diamond, 2013). Among individuals with eating disorders (EDs), neurocognitive deficits involving EFs (Kanakam & Treasure, 2013; van Elburg & Treasure, 2013) were reported, and a recent systematic review (Smith et al., 2018) highlighted the importance to consider the EFs in models concerning the risk of Eating Disorders, given the impairment in cognitive control, working memory, and attentional processes in population with eating disorder diagnosis. However, critical issues on the methodological quality of the studies and the high heterogeneity in methods, samples, and procedures did not lead to unique results (Cury et al., 2020), and to date, there are no clear models that identify the executive patterns of each EDs. The EFs are important also in healthy eating behavior because they affect behavioral response and preference toward healthy (i.e., low in fats, sugar, and calories) and unhealthy (i.e., hypercaloric food, characterized by high sugar and fats) food, and consequently can affect weight gain, with possible severe consequences on physical and general health status.

EFs alterations were reported in obesity condition, highlighting an association between excess adiposity and impairment of executive functions also in the absence of a diagnosis of ED (Favieri et al., 2019; Yang et al., 2018). According to these results, some studies developed preliminary conceptual models (e.g., Sellbom & Gunstad, 2012; Gettens & Gorin, 2017) to define the relationship between executive functions and obesity, in its psychophysiological and cognitive components. However, the lack of consensus in causality and progression of this relationship does not allow to assess the validity of these models.

Food intake represents one of the main causes of body gain. In the absence of metabolic dysfunctions and without a diagnosis of eating disorders, the tendency to overeat is associated with weight gain, justifying the high prevalence in the general worldwide population of overweight (WHO, 2020). In the current society, characterized by a food-abundant environment, the response to food stimuli may contribute to the tendency to overeat (Nijs et al., 2010). In fact, some authors reported in individuals who showed overeating behavior an increased approach toward food stimuli compared to non-food stimuli associated with inhibitory deficits or loss of control (Leehr et al., 2018). An altered response towards food stimuli has been reported in individuals with obesity (Favieri et al., 2019). For example, Stingl and colleagues (2012) highlighted worse working memory performance, assessed by a modified version of the n-back task adopting food stimuli, in individuals with obesity than individuals with healthy weight condition. Kulendran et al. (2017) reported an improvement of cognitive inhibition, evaluated with a modified version of the Stroop task with food stimuli, in a sample of individuals with severe obesity after bariatric surgery. Price and colleagues (Price, Lee & Higgs, 2016) highlighted poor response inhibition, assessed by a food-based Go/No-Go task in response to food stimuli in a sample of adults with overweight/obesity with low dietary restraint than individuals with normal weight. Moreover, in a sample of healthy undergraduate students, Calitri and colleagues (2010) found a predictive role of the performance in a Food Stroop task, adopting healthy and unhealthy food stimuli, on body weight increase. However, other studies on obesity (e.g., Bongers et al., 2011; Frank et al., 2014; Loeber et al., 2012; Phlan et al., 2011) did not confirm the same results. Once again, these divergent results may be due to heterogeneity in methods (Favieri et al., 2019; Favieri et al., 2020), which does not clarify the real role of food stimuli in the relationship between executive functions and eating behavior or weight condition.

Considering previous literature, this study aimed to clarify the role of food-related stimuli in the relationship between executive functions and weight status, adopting modified versions of EFs tasks (Favieri et al., 2019). To this end, a sample of healthy young adults with no eating disorder or significant overweight levels (i.e., BMI≤ 30) was considered. The difference in performance between healthy weight condition and moderate overweight was assessed using executive tasks with food-stimuli.

a) First, to justify the adoption of food tasks, the association between classic and modified versions was tested. Indeed, the discordance in previous studies on the association between executive functions and body weight may have been driven by the different versions of the tasks in measuring the same domain (Favieri et al., 2019).

b) Second, according to the studies reporting executive alterations in overweight participants (Favieri et al., 2019) and the sensitivity toward food-related tasks in the condition of overweight (Calitri et al., 2010; Nijs et al., 2010), the association between the performance in the executive tasks adopting food-stimuli, especially if high-palatable, and body-weight condition assessed by the body mass index (BMI) was evaluated (Brignell et al., 2009; Hou et al., 2011; Nijs et al., 2010). It was expected to confirm this association. Specifically, due to the high attraction of food, perceived as salient and arousing (Favieri et al., 2020), confirmed in both the general healthy population and individuals with maladaptive eating behavior or obesity, we expected a predictive role of the executive tasks on the BMI increase.

c) Lastly, according to the few studies reporting some alterations in specific EFs in response to food stimuli (Stingl et al., 2013; Price et al., 2016) in samples with obesity, we expected to find greater difficulty in people with overweight than a normal-weight condition in controlling the inhibitory responses toward food-related stimuli. Furthermore, we hypothesized better performance in working memory tasks when food stimuli than neutral stimuli are involved in the task.

Methods

Participants

The overall sample of participants was composed of one hundred and forty-four university students (age range: 18-30 years; mean age= 23.48± 2.85; 55 males, 89 female) recruited from "Sapienza" the University of Rome voluntarily. The 25.7% of the sample (37 on 144 participants) presented overweight condition (BMI range: 25-31; mean BMI= 27.19±2.86). The main characteristics of the overall sample are shown in Table 1.

Considering the low number of participants who presented overweight (N: 37; 18 males; 19 females; mean BMI= 27.19±2.86), a sub-group of students with normal-weight (N: 40; 20 males, 20 females; mean BMI= 21.63± 1.88), balanced for age and gender, was selected to test for differences in performance in the executive tasks between normal-weight and overweight conditions. The main characteristics of the group were shown in Table 2.

Table 1. Characteristics of the overall sample.

	N (%)
Demographic Information	
Sex	
Males	55 (38)
Females	89 (62)
Lifestyles Habits	
Smoking Habits	
Yes	55 (38)
No	89 (62)
Caffeine Consumption	
Yes	109 (76)
No	35 (24)
Alcohol Consumption	
Yes	81 (56)
No	63 (44)
Physical Activity	
Yes	70 (49)
No	74 (51)
Health Risk Factors: family diseases (yes)	
Dementia/ Mild Cognitive Impairment	28 (19)
Diabetes	68 (47)
Obesity	27 (19)
Cardiovascular Disorders	70 (49)
Hypertension	56 (39)

Table 2. Characteristics of the sample classified according to body weight condition

	Normal weight	Overweight	F	p	Pn2
N (m/f)	40 (20/20)	37 (18/19)			
Age (mean, sd)	24.33 (1.76)	24.73 (2.68)	< 1	0.43	0.01
Years of Education (mean, sd)	17.10 (1.66)	16.62 (1.85)	1.43	0.24	0.02
Physiological Measures (mean, sd)					
Weight (kg)	65.12 (9.36)	81.53 (14.79)	34.10*	0.0001	0.31
height (m)	1.73 (0.10)	1.73 (0.11)	< 1	0.97	0.00001
BMI	21.93 (1.88)	27.19 (2.86)	103.54*	0.0001	0.58
Weist-to-height ratio	0.45 (0.04)	0.51 (0.05)	35.75*	0.0001	0.34
Body Adiposity Index	26.20 (4.71)	32.09 (5.71)	22.66*	0.0001	0.25
Systolic Blood Pressure	119.58 (10.79)	119.86 (10.77)	< 1	0.91	0.00001
Dyastolic Blood Pressure	71.68 (8.33)	74.25 (7.28)	2.04	0.16	0.03
Heart Rate	78.05 (14.01)	75.46 (11.03)	< 1	0.38	0.01
Psychological Measures (mean, sd)					
TAS-20					
Difficulty in identifying feelings	13.08 (5.17)	13.88 (6.01)	< 1	0.60	0.005
Difficulty in describing feelings	12.35 (5.31)	13.71 (5.76)	< 1	0.37	0.02
Externally orienting thinking	15.46 (3.39)	15.51 (4.99)	< 1	0.97	0.0001
Total Score TAS-20	40.88 (11.82)	43.10 (11.96)	< 1	0.50	0.01
SCL-90					
Somatization	0.55 (0.45)	0.78 (0.73)	1.81	0.18	0.03
Obsessive-Compulsive	0.98 (0.58)	1.17 (0.79)	1.04	0.31	0.02
Interpersonal Sensitivity	0.57 (0.52)	0.75 (0.60)	1.33	0.25	0.02
Depression	0.75 (0.57)	1.19 (0.87)	4.65*	0.04	0.08
Anxiety	0.70 (0.49)	0.92 (0.71)	1.67	0.20	0.03
Anger-Hostility	0.45 (0.40)	0.52 (0.53)	< 1	0.59	0.006
Phobic Anxiety	0.19 (0.29)	0.21 (0.38)	< 1	0.76	0.002
Paranoid Ideation	0.71 (0.64)	0.53 (0.56)	1.25	0.27	0.02
Psychoticism	0.41 (0.48)	0.45 (0.45)	< 1	0.72	0.003
Global Index Severity	0.62 (0.43)	0.79 (0.53)	1.67	0.20	0.03
BDI					
Total Score	7.88 (6.41)	13.36 (8.44)	7.11*	0.01	0.12
STAI					
Total Score	45.35 (4.41)	46.64 (6.13)	< 1	0.38	0.01
BIS-11					
Attentional Impulsiveness	15.42 (3.07)	15.14 (3.50)	< 1	0.76	0.002
Motor Impulsiveness	19.92 (5.17)	19.04 (3.67)	< 1	0.47	0.01
Non-Planning Impulsiveness	24.73 (3.97)	23.68 (4.49)	< 1	0.83	0.37

Outcomes

- *Demographic information*

A semi-structured face-to-face interview was adopted to collect the participants' main demographic information (gender, age, level of education) and medical and clinical history.

- *Physiological measures*

A digital balance was adopted to assess the weight (Kg), and a wall-mounted anthropometer allowed measuring height (m). The body mass index (BMI) was computed by dividing weight by height (meters squared). The WHO criteria were adopted to classify weight status conditions (normal weight: BMI< 25 Kg/m2; overweight BMI > 25 Kg/m2; WHO, 2020).
A tape measure was adopted to assess waist and hip circumferences, to calculate the waist-to-height ratio (W/Hr; [36]) and body adiposity index (BAI = ((hip circumference)/((height)1.5)–18)); [37]). A digital sphygmomanometer was used to measure systolic and diastolic blood pressure.

- *Psychological Assessment*

Impulsivity: the Barratt Impulsiveness Scale (BIS-11) (Fossati et al., 2001) is a 30 items self-report questionnaire designed to assess general impulsiveness, considering the multifactorial nature of the construct. Attentional impulsiveness (attention and cognitive instability), motor impulsiveness (motor and perseverance), and non-planning impulsiveness (self-control and cognitive complexity) were evaluated.
Depression: the Beck Depression Inventory (BDI; Beck, 1996) is a 21 item self-report questionnaire adopted to assess depression. Depression level is evaluated on a scale from 0 to 63. Greater levels indicated a greater level of depression.
Anxiety: the State-Trait Anxiety Inventory (STAI, Spielberg et al., 1983) includes 40 items to assess anxiety. The items are rated on a four-point Likert scale, ranging from 1 (not at all) to 4 (very much so). In both the State and Trait anxiety scales, higher scores indicate greater anxiety levels. In this study, only trait anxiety was considered.
Psychological distress and symptomatology: the Symptom Checklist-90 (SCL-90; Derogatis, 1977): is a 90-items questionnaire aimed to assess psychological distress and symptomatology. The items are rated on a five-point Likert scale, ranging from 'not at all' (0) to 'extremely' (4). Primary symptoms of Somatization, Obsessive-Compulsive, Interpersonal Sensitivity, Depression, Anxiety, Anger-Hostility, Phobic Anxiety, Paranoid Ideation, and Psychoticism were assessed. A Global Severity Index provides measures of overall psychological distress. Higher scores in each dimension indicate greater distress and psychopathological symptomatology.

- *Executive Functions*

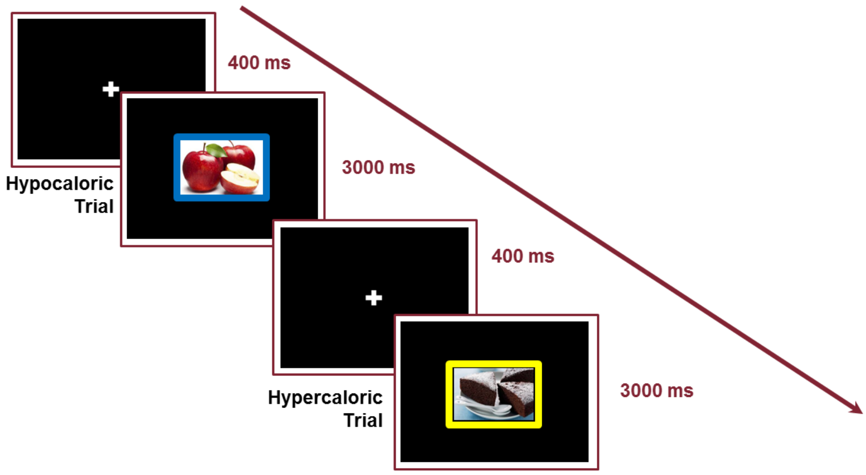
To assess the executive performance associated with food stimuli, the following tasks were adopted:
Apparatus: the computerized versions of the tasks were presented throughout the E-Prime 2.0 software on an Intel Core i5 PC and displayed on a 17-inch color screen. A computer keyboard collected the responses.

Food-Cue Tasks:

Picture Emotional Stroop Food-Cue (Hester et al., 2006): adopted to evaluate the interference control as an inhibition index.
Visual Stimuli and procedure: the task provided the administration of target stimuli consisted of colored pictures (300 x 300 pixels) from three different categories: objects (Neutral Condition; n= 6), high palatable

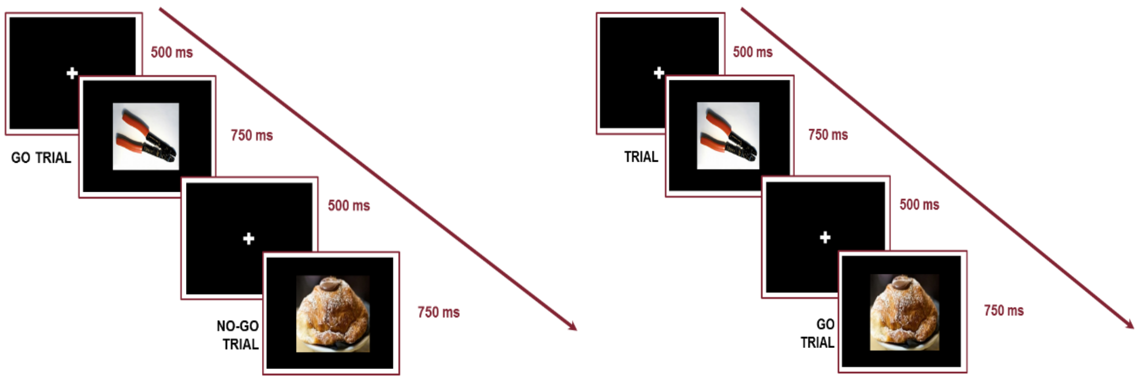
food (Hypercaloric Condition; n= 6), and low palatable food (Hypocaloric Condition; n= 6). The neutral stimuli were drawn from the International Affective Picture System (Lang et al., 1998). The food stimuli referred to pictures of traditional western meals, selected from a database of 61 images assessed by an independent sample of 54 undergraduate students considering valence, palatability, and satiety (on 0 to 10 rating-scale). High scores for the three indices indicated hypercaloric food (> 7.5), low scores indicated hypocaloric food (< 5.0). Each image had a colored frame. The colors were those used in the Stroop Task (i.e., YELLOW, RED, BLUE, GREEN). There were also six additional images constituted by a colored frame with no image in the center (Color Condition). Accordingly, each stimulus was randomly presented on the screen in the four possible color frames (in balanced order). The task required responding as quickly and accurately as possible by pressing the key corresponding to the color of the frame. The experiment was introduced by a practice block of 16 trials with feedback about correct execution. Afterward, two blocks of 144 randomly presented trials (24 for each category) were presented. An initial fixation cross (duration: 400 ms) was presented before each trial. The target stimulus remained on the screen for 3000 ms or until the participant's response. According to the aim of the study, mean reaction times (RTs) and percentage of accuracy for each condition were calculated, considering the correct responses with RT included between 200 and 2000 ms (according to Nijs et al., 2010). Moreover, the Conflict Effect Indices for Hypercaloric and Hypocaloric condition (mean RTs in Hypercaloric Trials – mean RTs in Neutral and Color Trials; mean RTs in Hypocaloric Trials – mean RTs in Neutral and Color Trials) for each participant were calculated. Figure 1 shows an example of the task procedure.

Figure 1. Picture Emotional Stroop Food-Cue Procedure.



Food Cue Go/No-Go Task (Price, Lee & Higgs, 2016) to assess motor inhibition in response to food stimuli. **Visual Stimuli and procedure**: the stimuli included two categories of pictures: neutral (do-it-yourself tools) selected from the IAPS and high palatable food selected from the same database adopted for the Stroop Task. Each picture was presented in the center of the screen with a black background. Two versions of the procedure were administered counterbalanced to each participant. In one version, the food stimuli represented the Go condition, and in the other version, the food stimuli represented the No-Go condition. The participant was required to fix the center of the screen for the duration of the experiment. The initial screen with a fixation cross (duration: 500 ms) was followed by the presentation of target stimuli (Go) and non-target stimuli (No-go), in a randomized way considering three, four, or five Go trials for each No-Go trial. Each stimulus remained in the center of the screen for 750 ms or until the participant’s response. The task required to press the left mouse key as quickly as possible when the picture associated with the Go condition appeared in the center of the screen. When the No-Go picture appeared, the participant had to wait for the disappearance of the stimulus. Each version of the task involved 200 trials divided into two blocks of 100 trials each. A practice block of 12 trials, with feedback on correctness, was presented at the beginning of the experiment. The inappropriate responses to "no-go" trials (36 for each Go/No-Go task) were summed to define the numbers of False Alarms, and the percentages of False Alarms ((no-go incorrect responses/total number of no-go trials) *100) on the Go Food and No-Go Food versions of the task were adopted as an index of the motor component of inhibition. Accuracy greater than 50% was accepted for including the participant in the analysis. Procedure and stimuli are shown in Figure 2.

Figure 2. Food Cue Go/No-Go Task



Food No-Go Procedure

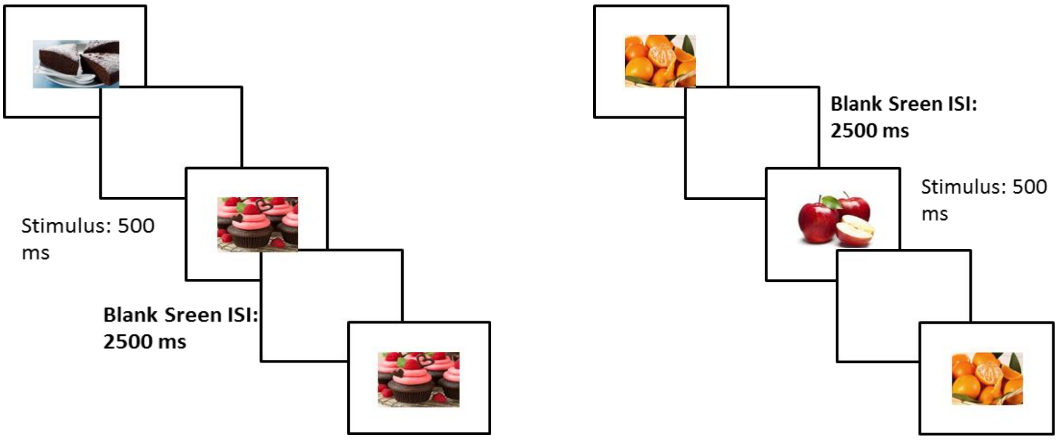
Food Go Procedure

Visual 1-Back and 2-Back Food Cue (Stingl et al., 2012): to assess working memory performance related to food cues.

Visual Stimuli and procedure: the stimuli included pictures of hypercaloric and hypocaloric food (extract from the same validated database used for the other tasks), presented in the center of the screen with a white background. The experiment consisted of two balance conditions according to the valence of the stimuli (Hypercaloric and Hypocaloric). For each condition of the task, two sessions were presented in sequence:

the one- and the two-back. A sequence of stimuli one-by-one (duration: 500 ms), followed by a blank screen (ISI: 2500 ms), was presented. In the one-back session, the participant evaluated whether each stimulus was the same (Target) or different (Non-Target) from the previous stimulus. In the two-back session, the participant had to indicate whether the stimulus was the same or different from the stimulus presented in the two previous trials. The responses were collected by pressing the key "X" for the target stimuli and the key "M" for the non-target stimuli. The Hypercaloric and Hypocaloric procedures include 40 trials for the one-back block and 40 trials for the two-back blocks. In each block the 30% of the trials were Target. The percentage of accuracy for both one-back and two-back procedures was considered as indices of working memory performance. Procedure and stimuli are shown in Figure 3.

Figure 3. Example of procedure of 1-back and 2-back task.



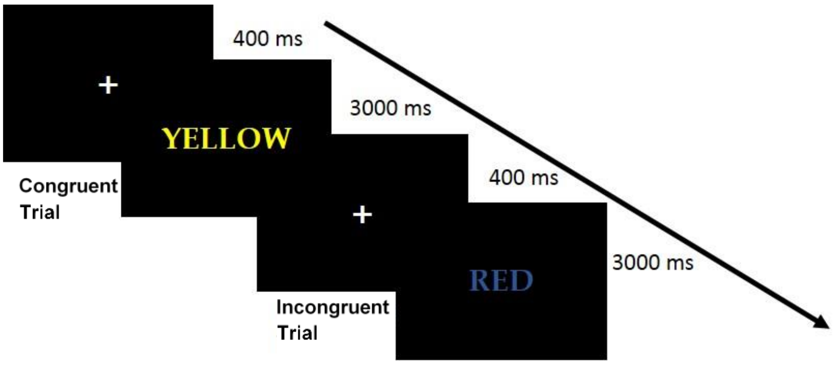
Hypercaloric 1-Back Trial Hypocaloric 2-Back Trial

Classic Tasks

The Stroop task (Stroop, 1935) is one of the most adopted instruments for assessing executive functions, specifically cognitive inhibition and interference control.

Visual Stimuli and procedure: the task provided the administration of target stimuli consisted of colored words (Font: Courier New; Font size: 60; colors: yellow, red, blue, green) referred semantically to the colors YELLOW, RED, BLUE, GREEN. Each word could be presented with the ink color related to its semantic meaning (Congruent Condition; e.g., RED wrote in red ink) or another color (Incongruent Condition; e.g., RED wrote in blue ink). As quickly and accurately as possible, the task required to press the key corresponding to the ink color (key “A”= red; Key “S”= green; Key “K”= blue; Key “L”= yellow). The experiment was introduced by a practice block of 15 trials with feedback about their correct execution. Afterward, a block of 120 randomly presented trials (60 Congruent and 60 Incongruent) was presented. An initial fixation cross (duration: 400 ms) was presented before each trial. The target stimulus remained on the screen for 3000 ms or until the participant's response. Reaction times (RTs) of correct responses were collected, and the Stroop Effect (mean RTs Incongruent Trials – mean RTs Congruent Trials) was computed. Procedure and stimuli are shown in Figure 1.

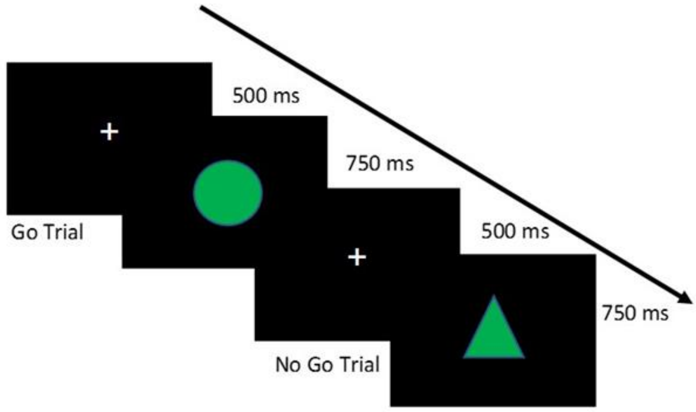
Figure 1. Example of stimuli and procedure of the Stroop Task



The Go/No-Go Task (Simson, Vaughan & Ritter, 1977) allows assessing motor inhibition, i.e., the ability to control an inadequate motor response.

Visual Stimuli and procedure: the stimuli included two geometric shapes of 960x720 pixels each, placed in the center of the screen with a black background. The Go stimulus was a green circle, and the No-Go stimulus was a green triangle. The participant was required to fix the center of the screen for the duration of the experiment. The initial screen with a fixation cross (duration: 500 ms) was followed by the presentation of target stimuli (Go) and non-target stimuli (No-go), in a randomized way considering three, four, or five Go trials for each No-Go trial. Each stimulus remained in the center of the screen for 750 ms or until the participant’s response. The task required to press the left mouse key as quickly as possible when the green circle appeared in the center of the screen. When the green triangle appeared, the participant had to wait for the disappearance of the stimulus. The task involved a total of 100 trials divided into two blocks of 50 trials each. A practice block of 12 trials, with feedback on correctness, was presented at the beginning of the experiment. The inappropriate responses to "no-go" stimuli were summed to define the numbers of False Alarms, considered the inhibition motor component. Procedure and stimuli are shown in Figure 2.

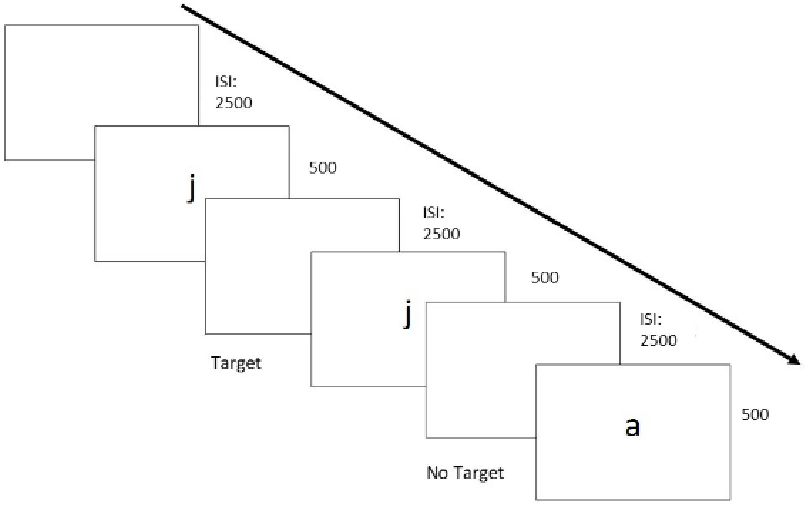
Figure 2. Example of stimuli and procedure of the Go/No-Go Task.



The n back task (Jaeggi et al., 2010) is largely adopted to assess working memory.

Visual Stimuli and procedure: the stimuli included some alphabetical letters presented in the middle of the screen (Font: Palatino Linotype; Font size: 30) with a white background. Two sessions of the task were presented in sequence: the one- and the two-back. A sequence of stimuli one-by-one (duration: 2500 ms), followed by a blank screen (ISI: 500 ms), was presented. In the one-back session, the participant evaluated whether each stimulus was the same as the previous stimulus (Target) or different from the previous stimulus (Non-Target). In the two-back session, the participant had to indicate whether the stimulus was the same or different from the stimulus presented in the two previous trials. The responses were collected by pressing the key "X" for the target stimuli and the key "M" for the non-target stimuli. The overall task includes 40 trials for the one-back block and 40 trials for the two-back blocks. In each block the 30% of the trials were Target. The percentage of accuracy for both one-back and two-back procedures was considered a measure of working memory. Procedure and stimuli are shown in Figure 3.

Figure 3. Example of stimuli and procedure of the N-Back Task (1-Back Version).



General Procedure

The research was conducted according to the Helsinki Declaration and the Local Ethics Committee (Department of Dynamic and Clinical Psychology and Health Studies —"Sapienza" the University of Rome; protocol n. 0000450- 15/04/2019) approved it. The written informed consent was explained, and participants signed it before the evaluation.

Each participant was individually tested in a silent, dimly illuminated room with a comfortable temperature, and the procedure was explained before the in-person interview. For each computerized version of the cognitive tasks, a practice block was included to allow the participant to become familiar with the task. Finally, weight, height, and blood pressure were measured, and questionnaires were administered.

Data Analysis

Means and standard deviations (i.e., continuous variables) and frequency and percentage (i.e., categorical variables) were collected for demographic, lifestyles, medical and physiological conditions, as well as for the cognitive tasks.

One-way ANOVAs were adopted to compare the two groups (Normal weight; Overweight) for each descriptive variable, psychological dimensions, and cognitive performance included in the study.

To verify the association between classical tasks and food-cue tasks, linear Pearson's r correlations were used to analyze the indices of the following tasks: Stroop Task (Stroop Effect on RTs), Go/No-Go Task (% of False Alarms), 1 and 2 back tasks (% of Accuracy) and the indices of Picture Emotional Stroop Food-Cue (RTs in Hypercaloric and Hypocaloric stimuli and the Hypercaloric and Hypocaloric Effect), Food-Cue Go/No-Go (% of false alarms in Go Food and No-Go Food version).

To verify the predictor role of the performance in the executive tasks adopting food cues for the BMI, single linear regression models for each task were calculated, as control linear regression models considering as predictor the indices of the classical tasks were also considered.

Finally, mixed ANOVAs were adopted to verify for each task the role of the food cues and the type of food cue in influencing the differences in the executive performance in the group.

For all the statistical analyses, the level of significance was accepted at $p < .05$. Statistical analysis was conducted using STATISTICA v10.0 and SPSS Statistics 25 software.

Results

The relationship between classical tasks and tasks adopting visual food stimuli

The linear Pearson's r correlations between classic and food-cue tasks in the overall sample are shown in Table 4. The indices of the different version of the Go/No-Go task were positively correlated (Classic-Go Food: $r= 0.56$; $p= 0.0001$; Classic- No-Go Food: $r= 0.51$; $p= 0.0001$), as well as the indices of the 2-Back tasks (Classic- Hypercaloric: $r= 0.57$; $p= 0.0001$; Classic- Hypocaloric: $r= 0.47$; $p= 0.0001$). Moreover, the

1-Back classic version was positively correlated with the 1-Back with hypocaloric cues (r= 0.37; p= 0.0001). Interestingly, the Stroop Task did not show significant Pearson's r correlation with the Picture Emotional Stroop Food-Cue, indicating that the two tasks, although often both reported as tasks assessing inhibitory control, probably measure different executive components (see Table 4).

Table 4. Pearson's r correlation between classic executive tasks and food-cue executive tasks.

		Picture Emotional Stroop Food-Cue									
Classical cognitive tasks		**RT_Hypercaloric**	**RT_Hypocaloric**	**Hypercaloric_Effect**	**Hypocaloric_Effect**	**Food Go**	**Food No-Go**	**1-Back Hypercaloric**	**1-Back Hypocaloric**	**2-Back Hypercaloric**	**2-Back Hypocaloric**
Stroop Effect	r	0.04	0.02	0.05	0.02	-0.0002	0.04	0.07	0.12	-0.17	-0.17
	p	0.69	0.86	0.60	0.86	0.99	0.69	0.48	0.23	0.09	0.09
False Alarms (%) Go/No-Go	r	0.14	0.08	-0.17	-0.21	**0.56**	**0.51**	-0.24	-0.20	-0.11	-0.12
	p	0.17	0.40	0.09	0.03	**0.0001**	**0.0001**	0.02	0.05	0.29	0.25
1-Back Task	r	0.09	0.13	0.001	0.10	-0.17	-0.09	0.11	**0.36**	0.001	**0.27**
	p	0.37	0.21	0.93	0.34	0.09	0.39	0.28	**0.0001**	0.99	**0.006**
2-Back Task	r	**-0.25**	**-0.28**	-0.09	**-0.21**	-0.01	-0.01	0.04	0.10	**0.57**	**0.47**
	p	**0.01**	**0.004**	0.33	**0.04**	0.93	0.91	0.67	0.33	**0.0001**	**0.0001**

The association between BMI and executive functions associated with food stimuli.

Different regression models were calculated to verify the single association between EFs performance and BMI changes. Specifically, faster RTs toward food cue (both hypercaloric and hypocaloric) in the Stroop task and higher accuracy in both the two version of the 2-back task (hypercaloric and hypocaloric) are associated with higher BMI (see Table 5). Considering Stroop Effect (R2= 0.002; t= 1.14; p= 0.26), % of false alarms (R2= 0.002; t= 0.46; p= 0.26) and 1-back (R2= 0.01; t= -1.17; p= 0.26) and 2-back accuracy (R2= 0.001; t= -0.16; p= 0.87) no association were found with BMI.

Table 5. Regression models with EFs performance as predictors and BMI as a dependent variable.

Models	**R^2 adjusted**	**F**	**B**	**Standard Error**	**beta**	**t**	**p**	**Zero-order correlation**
RTs to Hypercaloric stimuli	0.03	3.77	-0.01	0.004	-0.18	-1.94	0.05*	-0.18
RTs to Hypocaloric stimuli	0.03	3.97	-0.01	0.003	-0.18	-1.99	0.05*	-0.18
Food Go	-0.01	< 1	-0.006	0.03	-0.02	< 1	0.96	-0.02
Food No-Go	-0.003	< 1	0.02	0.03	0.08	< 1	0.40	0.08
1-Back hypercaloric	0.02	3.83	4.87	2.49	0.18	1.96	0.05*	0.18
1-Back hypocaloric	0.01	2.68	5.17	3.15	0.15	1.64	0.10	0.15
2-Back hypercaloric	0.03	4.08	3.67	1.82	0.18	2.02	0.05*	0.18
2-Back hypocaloric	0.03	4.13	3.60	1.77	0.19	2.03	0.04*	0.19

*significant predictor model.

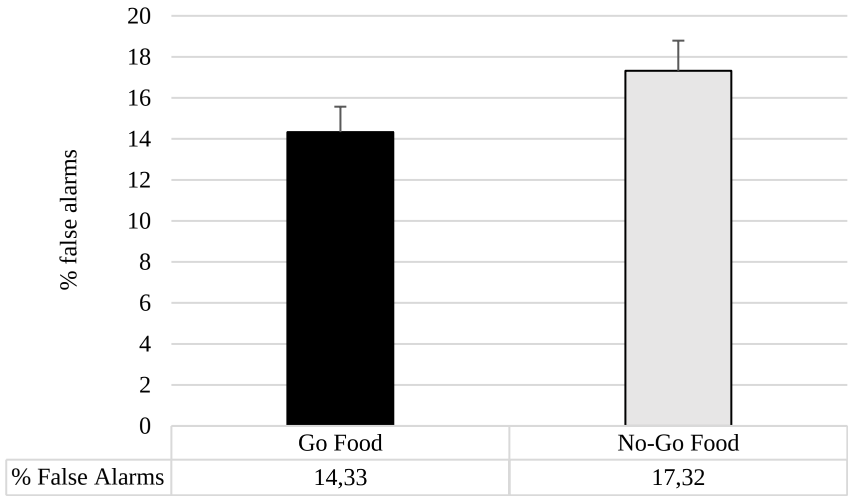
Analyses of variance (normal weight group vs. overweight group)

Considering the classic version of the executive tasks, no significant differences emerged between the two groups (see Table 6). Similar results were found by the mixed ANOVAs on the executive task adopting food cues, with no significant between-group differences ($F< 1$; $p> 0.20$). However, considering the Picture Emotional Stroop Food-Cue, a significant effect of the stimuli was highlighted ($F_{3.230}= 9.96$; $p= 0.0001$; $p\eta^2= 0.12$) with faster reaction times in color frame condition compared to the picture conditions (vs neutral: t= .3.09; p= 0.003; vs hypercaloric: t= -4.00; 0.0001; vs hypocaloric: t= -4.86; p= 0.0001), while no differences emerged between the three picture valences. No within-subject difference was present in the elaboration of the food-cue stimuli compared to the neutral one. The mixed ANOVA on the two versions of the Food Cue Go/No-Go reported a significant effect of the task ($F_{1,75}= 9.70$; $p= 0.003$; $p\eta^2= 0.14$). Generally, participants reported a higher percentage of false alarms in the motor inhibition toward the food stimuli (Food-No-Go) than toward the neutral stimuli (Food-Go) (see Figure 4). The Group and the Group x Task interaction were not significant ($F< 1$; $p> 0.60$). The analyses on the two versions of the visual 1-Back and 2-Back did not show significant effects for the group, the type of food, or the group x type of food interaction ($F< 1$; $p> 0.22$).

Table 6. Performance in the executive task of the two groups.

	Normal weight	Overweight	F	p	Pn2
Classic Executive Tasks					
Stroop Task Reaction Times					
Congruent condition	689.34 (73.94)	682.74 (78.60)	< 1	0.71	0.001
Incongruent condition	759.11 (87.01)	760.29 (93.60)	< 1	0.96	0.00001
Stroop Effect	69.78 (50.25)	77.55 (49.03)	< 1	0.50	0.01
Stroop Task % of accuracy					
Congruent condition	96.40 (0.92)	96.94 (0.97)	< 1	0.68	0.002
Incongruent condition	95.25 (6.81)	94.86 (5.67)	< 1	0.79	0.001
Go/No-Go Task					
% False Alarms	9.62 (7.64)	12.14 (7.62)	2.02	0.16	0.03
1-Back and 2-Back					
1-Back % Target Accuracy	94.97 (8.87)	93.86 (11.47)	< 1	0.37	0.01
2-Back % Target Accuracy	81.80 (17.61)	85.44 (14.05)	< 1	0.33	0.01
Executive Tasks with Food-Cue					
Picture Emotional Stroop Food-Cue Reaction Times					
Neutral Cue	712.23 (89.61)	695.48 (84.89)	< 1	0.43	0.01
Color Cue	688.36 (93.24)	690.83 (87.79)	< 1	0.91	0.00001
Hypercaloric Cue	709.18 (87.77)	700.59 (76.61)	< 1	0.67	0.003
Hypocaloric Cue	721.17 (102.19)	693.22 (84.20)	1.52	0.22	0.02
Hypercaloric Effect	-8.93 (34.29)	-7.44 (48.71)	< 1	0.88	0.0001
Hypocaloric Effect	-20.93 (7.43)	6.54 (7.42)	4.45	0.04	0.06
Picture Emotional Stroop Food-Cue % of accuracy					
Neutral Cue	96.43 (0.45)	97.03 (0.50)	< 1	0.37	0.01
Color Cue	96.73 (0.43)	98.74 (0.49)	2.39	0.13	0.03
Hypercaloric Cue	97.75 (0.60)	96.29 (0.68)	< 1	0.62	0.004
Hypocaloric Cue	97.25 (0.61)	95.45 (0.70)	1.89	0.17	0.03
Hypercaloric Effect	-0.18 (3.40)	1.11 (3.6)	2.34	0.13	0.03
Hypocaloric Effect	-0.15 (3.00)	1.93 (3.81)	6.49	0.01	0.09
Food Cue Go/No-Go Task % False Alarms					
Food Go Task	13.65 (8.73)	14.73 (10.92)	< 1	0.66	0.003
No-Go Task	16.20 (11.28)	16.94 (11.74)	< 1	0.79	0.001
Visual 1-Back and 2-Back Food Cue % of Target accuracy					
1-Back Hypercaloric	94.68 (15.95)	96.19 (6.63)	< 1	0.62	0.004
1-Back Hypocaloric	95.32 (6.70)	95.62 (6.70)	< 1	0.85	0.001
2-Back Hypercaloric	76.10 (21.72)	82.09 (16.24)	1.68	0.19	0.02
2-Back Hypocaloric	78.20 (20.19)	82.31 (15.21)	< 1	0.34	0.01

Figure 4. Mean and Std.Err of the performance in the two versions of Food-Cue Go/No-Go tasks.



Discussion

This study attempted to evaluate different unclear aspects evidenced by the association between weight status and executive functions. Specifically, the adoption of executive tasks with food stimuli and the executive performance were evaluated in their association with BMI in a non-clinical population with low to medium overweight levels.

In the literature, there is a debate on the usefulness of modified versions of the tasks to test the mediating role of food stimuli on the executive performances associated with weight status (Favieri et al., 2019). Accordingly, one of the first objectives of this study was to verify the association between the classical version of the tasks used to assess EFs and the modified versions of these tasks with food-related visual stimuli. Generally, tasks correlated only with their own modified version and partially with other executive tasks. According to Miyake's model (2000), this result suggests the possibility to evaluate them independently. A positive association between some executive tasks in the classic and food-cue versions emerged. Concerning the Go/No-Go task assessing motor inhibition and the 2-back task evaluating the working memory, the results suggest that the different versions of the task would evaluate the same domains, regardless of the stimulus type. However, different results were found for the Stroop task, considered the best tool to measure the inhibitory process (Zhang et al., 2018), and the Emotional Stroop with food stimuli. The emotional Stroop task was previously adopted to assess the inhibitory process (Arioli et al., 2020; Hester et al., 2010; Zhang et al., 2018); however, the studies are inconsistent in considering it a suitable tool for this purpose since certain differences emerged in the classic version of the task, due to aspects such as the types and the emotional content of the stimuli (Fisk & Haase, 2020), which can influence the sensibility of the instrument. This controversy also emerged for the modified versions of the Stroop with food cues (words or pictures). The Nijs and colleagues' study (2010) using a modified Stroop version with food stimuli (words) recorded a general attentional bias in both the early automatic (P200) and sustained (P300) phases of the attentional process (associated to cognitive control; Derryberry, 2002; Favieri et al., 2020) toward food stimuli, regardless of the participants' obesity status. Accordingly, Nijs and other authors (Calitri et al., 2010; Phlan et al., 2011) adopted the modified versions of the Stroop to analyze attentional bias rather than cognitive inhibition. Our study seems to confirm this dissociation between the two versions of the Stroop task that seem to assess a different level of cognitive control.

In this light, another interesting result concerns the association between executive performance and BMI. No relationship between BMI and executive functioning emerged considering the classical version of the Stroop task. Conversely, reaction times in the Stroop task using food-related stimuli (both hypocaloric and hypercaloric) and the accuracy in the 2-back task (both with hypercaloric and hypocaloric stimuli) predicted BMI. Considering the n-back task, our findings disagree with those reporting a worsening (Stingl et al., 2012) or no difference (Frank et al., 2014) in working memory performance when food stimuli are used to compare obesity and normal weight condition. Conversely, our results agree with Rutters and colleagues' findings showing that food stimuli are strongly represented in the working memory system, facilitating the task (Rutters et al., 2015). It was previously reported that the high reactivity to food could influence working memory (Hollit et al., 2010; Higgs, 2016). Accordingly, we might hypothesize that a greater attraction for food stimuli characterizes overweight and that working memory could modulate the visual attention toward food (Rutters et al., 2015). This hypothesis could explain why overeating behavior causes weight gain, at least in the first stage of overweight. This last aspect allows interpreting the results related to the Picture Emotional Stroop Food-Cue. If the previous results indicated that the Stroop with food stimuli would evaluate attentional mechanisms related to cognitive control, rather than cognitive inhibition, and if working memory could play a role in the processing of food-related stimuli, as suggested by Rutters (2015), the "fast reaction times - high BMI" association in case of food stimuli could be determined by the interaction between working memory and cognitive control. Furthermore, it should be noted that this pattern occurs in both highly palatable and hypocaloric stimuli, confirming the salient role of food regardless of its palatability (Favieri et al., 2020; Biehl et al., 2020), while the performance in the classical tasks showed an opposite associational pattern with the BMI, although no statistically significant. However, this interpretation should be taken with caution, and further studies should test mediating and moderating effect of the relationship between these variables in larger and better-distributed samples.

The final aim of the study was to analyze the differences between normal-weight and overweight conditions in executive performances toward food cues. A recent systematic review of the literature (Favieri et al., 2019) highlighted a general bidirectional relationship between excessive body weight and EFs, reporting an executive impairment associated with a more severe overweight condition. However, the review highlighted some limits of the literature, i.e., the few studies investigating the condition of the first stage of overweight (BMI< 30) and the heterogeneity in methods, which do not lead to clear results. Moreover, the role of food cues in executive function performance and the differences between different weight conditions are still unclear (Hendrikse et al., 2015; Hagan et al., 2020). Contrary to our hypothesis, in both the classical and the modified versions of tasks, no differences emerged between individuals with overweight and normal weight. Moreover, considering the Picture Emotional Stroop Food-Cue, neither between-group differences nor within-subject differences emerged considering the food-cue elaboration.

However, an interesting preliminary result was found considering the two versions of the Go/No-Go task. A within-subject difference emerged between the Go Food and No-Go food alternative versions of the task. Specifically, higher motor inhibition was reported in response to palatable food stimuli (in a task with many food stimuli) than neutral objects stimuli (in a task with few food stimuli). This result agrees with previous studies which reported similar inhibitory control pattern assessed by a Go/No-Go task in obesity and normal weight condition, suggesting that the salience of stimuli influences individuals with different weight conditions in a similar way (Loeber et al., 2012). Moreover, the results would suggest that the inhibitory response in an environment with a high density of food stimuli generates a greater difficulty in inhibiting overeating behavior. However, future studies are needed to clarify this aspect.

Limits and Conclusions

Although this study showed interesting preliminary results and was the first to integrate and compare different versions of cognitive tasks to assess the executive response toward food stimuli and its association with weight status, some limits should be highlighted. As already suggested, future studies should verify through designs using mediating and moderating variables the relationships highlighted by these preliminary results, particularly regarding the association between cognitive control, working memory, and BMI. In this study, the small sample size and the low percentage of overweight individuals (25.7 percent of the sample) did not allow for this analysis design. Furthermore, the low percentage of overweight individuals certainly reduced the statistical power of the results. The limitation of the sample should also be emphasized with respect to the comparison of the two groups, although this study reports a similar and sometimes higher sample size than previous studies on this topic (e.g., Loeber et al., 2012; Stingl et al., 2012; Nijs et al., 2010; Calitri et al., 2010). However, since this was a study on a healthy population with mild overweight levels, some results may not have emerged due to sample size. Another aspect that can be considered both a limitation and a starting point for future studies concerns the poor theoretical background on this topic, making this study preliminary both in its methodological framework and in the results obtained. Once again, it should be emphasized the importance of standardizing experimental protocols to verify the role of food-related stimuli in executive functioning, confirmed in studies on attentional bias (Favieri et al., 2019). Moreover, due to the discrepancies in the studies on the relationship between executive functions and overweight in the absence of pathological conditions, further studies should also focus more on this relationship across the lifespan (Favieri et al., 2019).

Another aspect that should be considered is the higher levels of anxiety and depression in people with overweight than in people with normal weight. This result observed in a healthy population confirms previous results observed in people with anxiety disorders and depression (Gariepy et al., 2010; Carey et al., 2014), and it should be investigated in a larger sample, evaluating whether such psychological conditions could influence the relationship between executive functioning and excessive weight. In conclusion, this study showed a possible role of the executive response toward food stimuli in weight gain. It contributes to a better understanding of the processes underlying BMI increase associated with dysfunctional eating behavior and may have applicative implications to prevent more severe overweight conditions. To counteract the weight gain from the first stage of overweight could help in reducing the negative trend of obesity prevalence occurring in recent years (WHO, 2020), stratified in all different cultures and all social and age groups.

CHAPTER 3. Overweight: the role of executive functions in BMI changes during the development

Introduction

Obesity is a relevant public health problem that increases directly or indirectly the risk of chronic diseases (e.g., cardiovascular pathologies, type-2 diabetes, hypertension, fibromyalgia) and psychological problems (i.e., depression, anxiety, psychopathological symptomatology) (WHO, 2020). Moreover, many data suggest that obesity is a risk factor for the development of neurocognitive decline, independently of age, education, general cognitive condition, and other lifestyle or health variables (Gettens & Gorin, 2017; Cserjesi et al., 2009; Prickett et al., 2015; Gunstad et al., 2007; Smith et al.., 2011).

The most recent European prevalence data reported that about 58 percent of the population over 18 years is affected by overweight with a range between 45 (Tajikistan) and 67 percent (Turkey) (from the gateway.euro.who.int; European Health Information Gateway; 2020). This percentage is confirmed in Italy, where 58 percent of the population over 18 years reported high body fat accumulation levels. Younger people (i.e., children and adolescents) are also characterized by an increase in overweight and obesity prevalence (Hernandez-Quevado & Rechel, 2018).

Usually, excessive body weight is strictly linked to a sedentary lifestyle and unhealthy eating habits (as the extreme assumption of hypercaloric food) (Calitri et al., 2010). However, a range of variables are associated with weight status, and one of the aspects that should be considered for a clear picture of obesity is its multifactorial etiology. Many biological (e.g., genetics, prenatal and perinatal aspects, neuroendocrine and physical conditions, autonomic and neurological characteristics), environmental (e.g., socioeconomic status, cultural and social biases, food availability), and behavioral (eating pattern, sedentary lifestyles, caloric intake, daily activities) factors concur to determine obesity (Kadouh & Acosta, 2017), from childhood (Kumar & Kelli, 2017) to the whole life span (Mehrzad, 2020). Accordingly, in these last years, the researchers focused on the role of cognitive processes in eating habits and related body weight changes (Yang et al., 2019; Favieri et al., 2020; Reinert et al., 2013; Smith et al., 2011). Many studies reported an association between cognitive deficits (involving memory, learning, attention, and executive functions) and excessive body weight, considering both overweight and obesity (Agusti et al., 2018; Yang et al., 2019; Favieri et al., 2020). Some researchers lead this association to a genetic vulnerability to overweight expressed in cognitive performances and alteration in brain morphology (Vainik et al., 2018). Other authors underlined a strong bidirectional relationship between cognitive impairment and increased body weight with an important role played by the Executive Functions (EFs; Gettens & Gorin, 2017; Favieri et al., 2019; Davidson et al., 2019). This last association is confirmed in people of different ages (for a review, see Favieri et al., 2019).

Early association between obesity and EFs impairment was supported (Wirt et al., 2015; Smith et al., 2011), specifically considering inhibition (Mamrot & Hanc, 2019). A worsening of executive functioning from young adulthood and late adulthood was also confirmed (Smith et al., 2011). However, no studies analyzed the trend of the association considering both children and young adults to verify whether, independently from age, the EFs could have a predictive role in weight increase and to understand which of them (according to Diamond's model; 2013) is mainly involved in this relationship. Again, few studies focused on overweight in the absence of pathological conditions, such as obesity (Gunstand et al., 2010; Coppin et al., 2014). This limit could be due to the indices adopted to assess weight status in young and adults. One of the most adopted measures, in both clinical and research fields, is the body mass index (BMI; WHO, 2020), which presents some limits in identifying the risk associated with excessive body weight, specifically in younger (Lee, Huxley, Wildman & Woodward, 2008). Some authors have attempted to be overcome this limit by adopting reference charters referring to the general population (De Onis et al., 2007; De Onis et al., 2007). However, these limitations have prevented studies from including populations of children and adolescents.

This study analyzes the association between weight status and EFs considering a sample including children, adolescents, and young adults from the general population, without pathological obesity and eating disorders. According to previous studies, we hypothesized a general association between the increased body weight and worse performance in executive tasks, independently from age (Favieri et al., 2019). Moreover, in line with EFs development models during life (Zelazo & Muller, 2011), we expected a different involvement of the single EFs considering children, adolescents, and young adults.

Methods

Participants

One-hundred and sixty-six students (65 males and 101 females; mean age: 17.06 years SD = 6.55) were recruited from different Italian public schools to participate in the study. Specifically, 46 children were from first grade of education (age range: 7-11; 22 males, 24 females; mean age: 7.98 years SD= 0.88), 50 adolescents come from the high school (age range: 15-18; 15 males, 35 females; mean age: 16.64 years SD= 0.75), 70 young adults were from college (age range: 19-30; 31 males, 42 females; mean age: 23.32 years SD= 2.57).

The participants were included in the study if they did not present eating disorders diagnosis, severe obesity condition, developmental disorders, chronic medical diseases, or any psychopathological conditions (e.g., anxiety, depression). Moreover, a normal or corrected-to-normal vision and the absence of color blindness were required.

Of the overall sample, 59 participants (20 males, 39 females) presented a condition of overweight, and 107 participants (49 males, 62 females) presented a condition of normal weight according to WHO weight classification both for children and adolescents and adults (WHO, 2020).

Table 1 shows the main characteristics of the participants considering age and weight classification.

Table 1. Characteristics of participants and performances in the EFs tasks.

	Children		Adolescents		Young Adults			
	Normal weight	Overweight	Normal weight	Overweight	Normal weight	Overweight	F	p
N (m/f)	31 (17/14)	15 (5/10)	38 (13/25)	12 (2/10)	38 (15/23)	32 (13/19)		
Age	8.00 (0.93)	7.93 (0.80)	16.71 (0.77)	16.42 (0.67)	22.39 (2.28)	24.44 (2.47)	8.12	0.001
Years of Education	2.90 (0.75)	2.93 (0.80)	11.71 (0.77)	11.42 (0.67)	15.89 (1.33)	16.84 (1.22)	5.36	0.01
Weight (kg)	27.79 (5.35)	38.24 (7.96)	58.10 (7.38)	75.33 (11.36)	61.45 (8.78)	80.03 (15.18)	2.39	0.10
Hight (m)	1.32 (0.08)	1.35 (0.07)	1.68 (0.07)	1.68 (0.11)	1.69 (0.09)	1.70 (0.08)	< 1	0.59
BMI	15.83 (1.70)	20.74 (3.00)	20.46 (1.97)	26.74 (3.30)	21.34 (1.74)	27.35 (3.05)	< 1	0.37
BMI/age ratio	1.99 (0.23)	2.64 (0.43)	1.23 (0.13)	1.63 (0.22)	0.97 (0.13)	1.11 (0.13)	20.78	0.001
Weist-to-height ratio	0.45 (0.04)	0.50 (0.06)	0.40 (0.08)	0.47 (0.04)	0.43 (0.04)	0.50 (0.10)	< 1	0.72
Body Adiposity Index	24.56 (4.52)	29.61 (6.43)	20.48 (8.59)	26.18 (5.67)	21.23 (3.13)	26.82 (9.79)	< 1	0.97
Systolic Blood Pressure	108.52 (17.71)	113.65 (7.55)	104.75 (12.36)	111.41 (12.48)	114.42 (10.68)	119.39 (11.46)	< 1	0.95
Dyastolic Blood Pressure	67.74 (11.14)	76.25 (10.73)	68.16 (7.13)	72.54 (7.74)	69.30 (8.30)	74.70 (6.84)	<1	0.61
Hunger (0-100)	50.80 (33.83)	37.17 (27.05)	40.28 (34.63)	45.83 (31.48)	61.06 (26.65)	45.13 (33.63)	1.40	0.25
Inhibition								
Stroop Effect (Stroop Task index on RT)	91.96 (81.22)	108.23 (82.46)	66.59 (44.94)	103.61 (63.78)	91.91 (60.18)	98.24 (69.83)	< 1	0.53
False Alarms (Go-No Task index	7.74 (4.15)	8.83 (5.20)	4.66 (3.53)	5.67 (4.08)	3.97 (3.14)	4.55 (2.79)	< 1	0.92
Working memory								
1-back task accuracy (%)	0.70 (0.28)	0.72 (0.25)	0.93 (0.10)	0.88 (0.13)	0.94 (0.10)	0.93 (0.11)	< 1	0.60
2-back task accuracy (%)	0.50 (0.27)	0.51 (0.24)	0.67 (0.22)	0.71 (0.21)	0.79 (0.17)	0.82 (0.21)	< 1	0.98
Shifting								
Global Score (WCST)	33.63 (20.98)	37.47 (16.90)	21.13 (16.62)	25.17 (19.09)	16.63 (16.01)	13.16 (10.85)	< 1	0.70
Perseveration (WCST)	10.50 (9.05)	11.93 (10.44)	6.03 (3.74)	7.92 (4.91)	4.87 (4.21)	4.38 (3.59)	< 1	0.61

Outcomes

Apparatus

A digital balance was used to assess each participant's weight (Kg), and a wall-mounted anthropometer was adopted to measure the height (m). These two measures allow computing the body mass index (BMI), dividing weight by height (meters squared). The WHO criteria were adopted, considering the growth charts for children and adolescents (WHO, 2020) and the BMI classification for young adults (WHO, 2020).

A tape measure was adopted to measure waist and hip circumferences, useful to calculate the waist-to-height ratio (W/Hr; Maffeis et al., 2008) and body adiposity index (BAI = ((hip circumference)/((height)1.5)–18)); Bergman et al., 2011). A digital sphygmomanometer was used to measure systolic and diastolic blood pressure.

Demographic information

A semi-structured interview was adopted to collect each participant's main demographic information (gender, age, level of education) and medical and clinical history. For children and adolescents under 18 years of age, the interview was conducted by one of the parents.

Executive functions

According to Diamond's model (2012), executive functions were assessed in all age groups; standardized tasks previously adopted in childhood, adolescence, and adulthood were used.

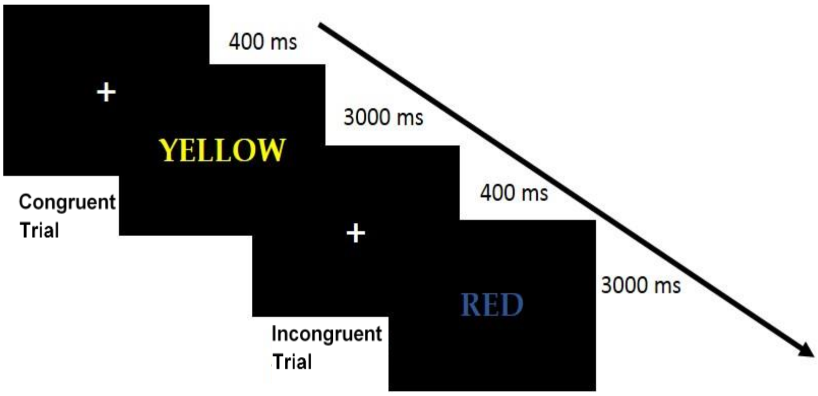
Apparatus: computerized versions of the Stroop task, Go/No-go task, and n back task were presented throughout the E-Prime 2.0 software on an Intel Core i5 PC and displayed on a 17-inch color screen. A standard computer keyboard collected the responses.

Inhibition:

- *The Stroop task* (Stroop, 1935) is one of the most adopted instruments for assessing executive functions, specifically cognitive inhibition and interference control.

Visual Stimuli and procedure: the task provided the administration of target stimuli consisted of colored words (Font: Courier New; Font size: 60; colors: yellow, red, blue, green) referred semantically to the colors YELLOW, RED, BLUE, GREEN. Each word could be presented with the ink color related to its semantic meaning (Congruent Condition; e.g., RED wrote in red ink) or another color (Incongruent Condition; e.g., RED wrote in blue ink). As quickly and accurately as possible, the task required to press the key corresponding to the ink color (key "A"= red; Key "S"= green; Key "K"= blue; Key "L"= yellow). The experiment was introduced by a practice block of 15 trials with feedback about their correct execution. Afterward, a block of 120 randomly presented trials (60 Congruent and 60 Incongruent) was presented. An initial fixation cross (duration: 400 ms) was presented before each trial. The target stimulus remained on the screen for 3000 ms or until the participant's response. Reaction times (RTs) of correct responses were collected, and the Stroop Effect (mean RTs Incongruent Trials – mean RTs Congruent Trials) was computed. Procedure and stimuli are shown in Figure 1.

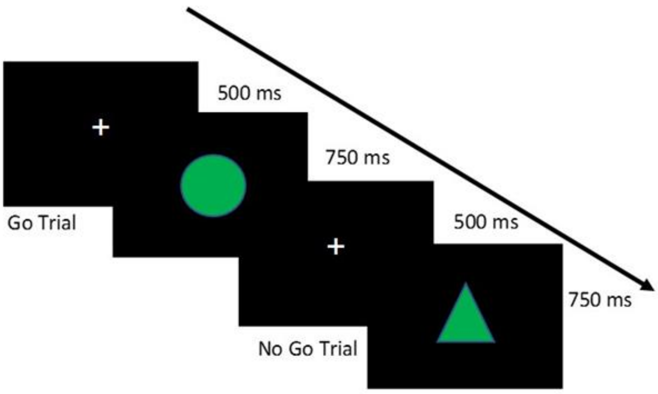
Figure 1. Example of stimuli and procedure of the Stroop Task



- *The Go/No-Go Task* (Simson, Vaughan & Ritter, 1977) allows assessing motor inhibition, i.e., the ability to control an inadequate motor response.

Visual Stimuli and procedure: the stimuli included two geometric shapes of 960x720 pixels each, placed in the center of the screen with a black background. The Go stimulus was a green circle, and the No-Go stimulus was a green triangle. The participant was required to fix the center of the screen for the duration of the experiment. The initial screen with a fixation cross (duration: 500 ms) was followed by the presentation of target stimuli (Go) and non-target stimuli (No-go), in a randomized way considering three, four, or five Go trials for each No-Go trial. Each stimulus remained in the center of the screen for 750 ms or until the participant's response. The task required to press the left mouse key as quickly as possible when the green circle appeared in the center of the screen. When the green triangle appeared, the participant had to wait for the disappearance of the stimulus. The task involved a total of 100 trials divided into two blocks of 50 trials each. A practice block of 12 trials, with feedback on correctness, was presented at the beginning of the experiment. The inappropriate responses to "no-go" stimuli were summed to define the numbers of False Alarms, considered the inhibition motor component. Procedure and stimuli are shown in Figure 2.

Figure 2. Example of stimuli and procedure of the Go/No-Go Task.

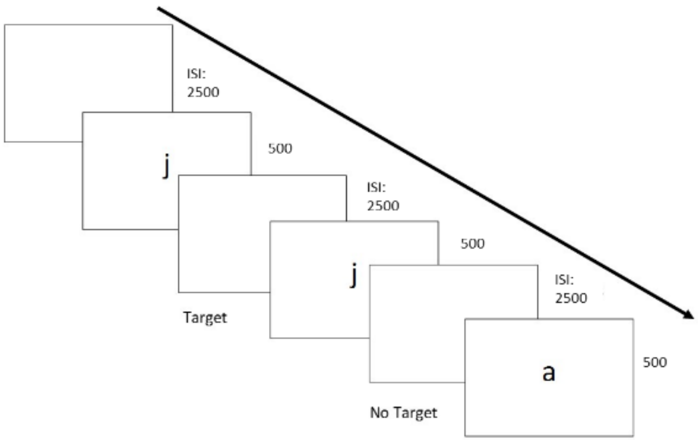


Working Memory:

- *The n back task* (Jaeggi et al., 2010) is largely adopted to assess working memory.

Visual Stimuli and procedure: the stimuli included some alphabetical letters presented in the middle of the screen (Font: Palatino Linotype; Font size: 30) with a white background. Two sessions of the task were presented in sequence: the one- and the two-back. A sequence of stimuli one-by-one (duration: 2500 ms), followed by a blank screen (ISI: 500 ms), was presented. In the one-back session, the participant evaluated whether each stimulus was the same as the previous stimulus (Target) or different from the previous stimulus (Non-Target). In the two-back session, the participant had to indicate whether the stimulus was the same or different from the stimulus presented in the two previous trials. The responses were collected by pressing the key "X" for the target stimuli and the key "M" for the non-target stimuli. The overall task includes 40 trials for the one-back block and 40 trials for the two-back blocks. In each block the 30% of the trials were Target. The percentage of accuracy for both one-back and two-back procedures was considered a measure of working memory. Procedure and stimuli are shown in Figure 3.

Figure 3. Example of stimuli and procedure of the N-Back Task (1-Back Version).



Shifting

- The *Wisconsin Card Sorting Test* (WCST, Milner, 1963), a computerized version of the WCST was adopted to assess cognitive flexibility. The test requires the participant to match some cards according to specific characteristics of four Stimulus Cards.

Visual Stimuli and procedure: two sets of 64 cards were presented. There are four possible suits in the cards (i.e., stars, crosses, circles, triangles), they can be of four possible colors (i.e., red, yellow, green, blue) and each card can have a different number of suits, from 1 to 4. The cards are sorted by referencing four stimulus cards with one red triangle, two green stars, three yellow crosses, four blue circles. The participant has to place a single card of the deck in correspondence with one of the four initial stimulus cards. At each participant's choice, the experimenter provides feedback on the correctness of the answer to allow the participant to infer the adopted criterion (i.e., color, shape, number, respectively) to sort the cards through this feedback ignoring the other criteria. This procedure continues until the participant makes ten correct choices. Then the correct answer criterion changes. The procedure continues until the two decks of cards are completed. Different indices can be extrapolated from the test. In this study, the global score ([card administered - (completed categories*10)] with lower scores as indices of better performance) and perseveration errors (as an index of difficulty in shifting the procedure to complete the task).

General Procedure

The research was conducted according to the Helsinki Declaration and the Local Ethics Committee (Department of Dynamic and Clinical Psychology—"Sapienza" the University of Rome; protocol n. 0000450- 15/04/2019) approved it. The written informed consent was signed before the evaluation by each participant, parents signed the consent for children, and both participants and their parents signed the consent for adolescents.

Each participant was individually tested in a silent, dimly illuminated room with a comfortable temperature. Before the experimental session, the procedure was explained to all participants; then, they were subjected to the face-to-face socio-anamnestic interview. Subsequently, the participant indicated the current hungry levels on a visual-analogue scale (0–100 mm) and completed the experimental tasks. Finally, weight, height, and blood pressure were measured.

Data analysis

Data are reported as means and standard deviations for each age group (children, adolescents, and young adults) and the weight condition (normal weight, overweight). Two-way ANOVAs were carried out to control the differences between groups considering each variable. Furthermore, a hierarchical multiple linear regression was carried out on the whole sample to evaluate the role of executive functions on BMI variation, considering the task assessing the three EFs of Diamond's model (inhibition, working memory, and shifting) in line with the aim of the study. BMI to age ratio was calculated to control for the greater impact of high BMI in younger ages. Age was added as a covariate in the regression model to control its role in the relationship among variables to control its role in the relationship among variables. The 3 steps assessed in the hierarchical multiple linear regression model were: (1) cognitive inhibition: including false alarms on the Go/No-go task and Stroop effect (RT) indices; (2) working memory: including accuracy at the one and two-back; (3) shifting: including global score and perseverations on the WCST. To assess the association between weight condition (BMI, waist-to-height ratio, Body adiposity index) and executive functioning in the different age groups, sub-groups linear Pearson's r correlations were calculated, and Benjamini-Hochberg correction for the p-value was included.

Results

General data of the sample

Table 1 shows the sample's main characteristics (means and std.dev.) classified according to age and weight condition. Also, the performance of the groups in executive tasks is shown.

Regression analysis

The hierarchical regression model adjusted for age was significant (see table 2). The best model considered the inhibition indices (Stroop Effect and False Alarms) ($F_{2,160}$= 5.49; p= 0.005; Adjusted R^2= 0.73). Specifically, considering the predictors of the models, only False Alarms on the Go/No-Go task were related to increased age-adjusted BMI.

Table 2. Hierarchical regression model considering the BMI/age index as a dependent variable (adjusted for age).

	Models	B	Standard Error	Beta	t	Sign. (p=)	95% CI lower	95% CI upper	zero-order correlation	% of explenation
1	Stroop Effect	0.00	0.000	0.04	0.99	0.33	0.0	0.001	0.10	72
	False Alarms	**0.01**	**0.006**	**0.14**	**2.94**	**0.004**	**0.006**	**0.03**	**0.48**	
2	Stroop Effect	0.0	0.000	0.04	0.93	0.35	0.0	0.001	0.10	73
	False Alarms	**0.02**	**0.007**	**0.14**	**2.94**	**0.004**	**0.006**	**0.03**	**0.48**	
	1-back task accuracy	-0.17	0.145	-0.06	-1.14	0.25	-0.45	0.12	-0.42	
	2-back task accuracy	0.16	0.115	0.07	1.35	0.18	-0.07	0.38	-0.41	
3	Stroop Effect	0.0	0.000	0.04	0.88	0.38	0.0	0.001	0.10	73
	False Alarms	**0.02**	**0.007**	**0.14**	**2.92**	**0.004**	**0.006**	**0.03**	**0.48**	
	1-back task accuracy	-0.14	0.148	-0.05	-0.96	0.34	-0.43	0.15	-0.42	
	2-back task accuracy	0.15	0.116	0.07	1.33	0.19	-0.07	0.38	-0.41	
	Global Score (WCST)	0.002	0.002	0.06	0.91	0.36	-0.002	0.006	0.42	
	Perseveration (WCST)	-0.001	0.01	-0.01	-0.14	0.89	-0.012	0.01	0.36	

Table 3. Intercorrelations of cognitive measures included in the regression model.

	Age-Adjusted BMI	Stroop Effect	False Alarms	1-back task	2-back task	Global Score WCST	Perseveration WCST
Stroop Effect	0.08	1.00					
False Alarms	0.48*	0.17**	1.00				
1-back task	-0.42*	-0.07	-0.32*	1.00			
2-back task	-0.41*	-0.03	-0.32*	0.54*	1.00		
Global Score WCST	0.42*	0.06	0.19**	-0.32*	-0.27*	1.00	
Perseveration WCST	0.36*	0.12	0.13	-0.25*	-0.29*	0.74*	1.00

*p< 0.0001; **p< 0.01

Correlation analysis

Tables 4, 5, and 6 reported linear Pearson's r correlation in the three different age groups considering the weight indices of BMI, waist-to-height ratio, Body adiposity index, and self-reported hunger before the EF task administration.

Specifically, in children, no significant correlations were found (Table 4).

In adolescents, BMI was correlated with worse performance in WCST considering both global score (r= 0.43; p= 0.02) and perseveration (r= 0.41; p= 0.03). Moreover, positive linear correlations were reported between self-reported hunger and the false alarms index (r= 0.55; p= 0.003) and lower accuracy on the 1-back task (r= -0,39; p= 0.05) (Table 5).

In the young adults' group, the only significant correlation was between BMI and false alarms in the Go/No-go task (r= 0.28; p= 0.05) (Table 6).

Table 3. Pearson's r correlations in children

		Stroop Effect (Stroop Task)	*False Alarms (Go-Nogo Task)*	*1-back accuracy*	*2-back accuracy*	*Global score (WCST)*	*Perseveration (WCST)*
BMI	R	0.07	0.15	0.15	0.21	-0.01	0.02
	P	0.60	0.37	0.37	0.20	0.98	0.88
waist-to-height	R	-0.04	-0.05	0.28	0.24	0.04	-0.03
	P	0.82	0.75	0.08	0.14	0.83	0.84
BAI	R	0.16	0.18	0.24	0.21	-0.10	-0.19
	P	0.32	0.27	0.13	0.19	0.55	0.23
Sense of hunger	R	-0.03	-0.13	-0.17	-0.20	0.13	-0.02
	P	0.86	0.42	0.30	0.24	0.41	0.91

Adjusted critical p-value (Benjamini-Hochberg correction) = 0.01.

Table 4. Pearson's r correlations in adolescents

		Stroop Effect (Stroop Task)	False Alarms (Go-Nogo Task)	1-back accuracy	2-back accuracy	Global score (WCST)	Perseveration (WCST)
BMI	R	-0.05	-0.28	-0.001	0.11	**0.43**	**0.41**
	P	0.81	0.16	0.98	0.60	**0.02***	**0.03***
waist-to-height	R	0.06	0.12	-0.08	0.04	0.30	0.29
	P	0.75	0.55	0.69	0.86	0.13	0.14
BAI	R	0.02	0.12	-0.03	-0.01	0.24	0.22
	P	0.90	0.54	0.88	0.94	0.24	0.27
Sense of hunger	R	0.18	**0.55**	**-0.39**	-0.06	-0.11	-0.13
	P	0.38	**0.003***	**0.05***	0.76	0.57	0.52

Adjusted critical p-value (Benjamini-Hochberg correction) = 0.03 (*significant correlations).

Table 5. Pearson's r correlation in young adults

		Stroop Effect (Stroop Task)	False Alarms (Go-Nogo Task)	1-back accuracy	2-back accuracy	Global score (WCST)	Perseveration (WCST)
BMI	R	0.05	**0.28**	-0.23	0.14	-0.16	-0.18
	P	0.75	**0.05***	0.10	0.33	0.25	0.20
waist-to-height	R	-0.07	0.13	-0.10	0.05	-0.04	-0.05
	P	0.64	0.36	0.48	0.74	0.79	0.73
BAI	R	0.04	0.14	-0.15	0.08	0.07	0.03
	P	0.79	0.34	0.30	0.58	0.61	0.81
Sense of hunger	R	0.01	0.06	-0.12	-0.10	0.13	0.14
	P	0.92	0.66	0.41	0.51	0.35	0.33

Adjusted critical p-value (Benjamini-Hochberg correction) = 0.01.

Discussion

Many previous studies have associated excessive body weight with worse performance in EFs (Favieri et al., 2019; Yang et al., 2019). Some findings suggested that EFs (including inhibitory control, shifting, and working memory; Diamond, 2013) may play a moderator role in the relationship between the intention and the act of eating, influencing the real intake of food (Gettens & Gorin, 2017; Nederkoorn et al., 2010). Therefore, EFs would explain the weight condition. Accordingly, different authors developed preliminary conceptual models (e.g., Sellbom & Gunstad, 2012; Gettens & Gorin, 2017) to define the relationship between EFs and obesity. However, there is still a lack of consensus about the nature of this relationship and its evolution during the life span, especially in children and adolescents (Favieri et al., 2019; Groppe & Elsner, 2015).

This study was aimed to define a possible relationship between weight condition and executive functioning, according to Diamond's tripartite model (2013), which organized the EFs in three main domains: working memory updating, shifting, and inhibition. The results confirmed an association between one of the EFs'domain, i.e., inhibition, and the BMI. A predictive role on weight gain of motor inhibition was highlighted. According to previous studies, higher BMI, adjusted for age, is related to worse performance in a task - the Go/No-Go Task -assessing motor inhibitory control (Wessel, 2017). This result could suggest that the inhibition effectively plays an important role in controlling the eating behavior that influences body weight, starting from not severe conditions and independently from age. This assumption would agree with previous studies that reported similar results in children (Reyes et al., 2015). Moreover, studies that did not observe worse performance in overweight but only in obesity in other phases of development (e.g., Alarcon et al., 2016; Hendrick et al., 2012; Verdejo-Garcia et al., 2010) were disconfirmed. Surprisingly, this association did not emerge when the Stroop task assessed the cognitive component of the inhibition (cognitive control). The discrepancy between the two measures of inhibition can be explained by the different neural networks, associated with the different component of inhibition, involved in the two tasks (Bernal & Altman, 2009), and it is in line with previous studies that reported alteration in the cortical motor areas in individuals with obesity (Stice et al., 2016). It would be interesting to detect further whether the implication of the motor component of inhibition could represent the origin of the inability to inhibit eating behavior as a possible genesis of obesity, or whether the worse performance in the task assessing motor inhibition reflects a first impairment caused by a slight increase of body fat associated with overweight. Interestingly, in our sample, no predictive role of the other EFs on BMI increase was highlighted, but interesting assumptions emerged considering the correlational results in the different age groups.

In fact, another specific goal of the study was to verify whether this relationship could emerge, on the net of age, in a sample including children, adolescents, and young adults with normal or overweight conditions but without obesity or any other health disorders such as medical conditions, psychopathologies, developmental diseases, maladaptive eating behaviors. The results appear to confirm this hypothesis. According to previous studies, obesity is generally associated with worse executive performance in the lifespan (for a review, see Favieri et al., 2019). However, if the studies considered only the overweight, i.e., a bodyweight not exceeding the critical cut-off for obesity (BMI< 30 kg/m^2), this association is not always confirmed in both adults (e.g., Hendrick et al., 2012; Gonzales et al., 2010; Yadava and Sharma, 2014) and adolescents (e.g., Alarcon et al., 2016; Fields et al., 2013; Verdejo-Garcia et al., 2010). Moreover, only a few studies have examined EFs in children with obesity, mainly focused on inhibition and generally ignored the other EFs (Groppe & Elsner, 2015; Reyes et al., 2015; Reinert et al., 2013), and indicating an impairment in the inhibitory control in obesity. However, this impairment was not confirmed considering the other EFs (Gunstad et al., 2007; Li et al., 2008). Determining whether high body weight is associated with impaired EFs in children and adolescents is fundamental to defining the trend of the relationship over time.

The lack of studies on this topic is due to multiple reasons. One of these is related to the absence of an index of body weight condition adequate for the different ages. In fact, some limitations of the BMI have been recently emphasized, and it was reported that it is not a good indicator of disease risk in overweight (e.g., in the case of metabolic and cardiovascular alteration), for its high cross-gender and cross-cultural variations (Choi et al., 2018). However, also the other alternative indices of body composition (e.g., waist-to-high ratio; body adiposity index) presented some limits (Lo, Wong, Khalechelvam & Tam, 2016; Fedewa, Nickerson & Esco, 2020), and further studies needed to find a consensus on better indices of risk associated to excessive body adiposity and body weight (Tutunchi et al., 2020), and to overcome this gap. For these reasons and given that an identical BMI might indicate a greater risk of overweight in children than in young adults, this study considered BMI in proportion to age.

The study results highlighted that no significant correlations were observed between the weight indices and the EFs performance in children. Considering that few studies considered these relationships in children and mainly focused on the obesity condition (Favieri et al., 2019), the absence of significant results should be clarified. During the first years of life and until adolescence, the brain undergoes structural changes and development in the neural organization (Miller, Lee & Lumeng, 2015). These physiological changes may not clearly identify the associational pattern between EFs performance and excessive body weight, covering the alteration in the executive functioning associated with excessive body weight. Moreover, if we assume that executive functions may drive eating behavior, this relationship could not emerge in children because their diet is more controlled by the parents (Scaglioni et al., 2008; Mitchell et al., 2013).

The present results highlighted that poor cognitive flexibility, assessed by WCST, is associated with higher BMI in adolescents. This result contrasts with a previous study that did not report significant differences between adolescents with normal weight and overweight (Delgado-Rico et al., 2012). However, previous research reported that adolescents with eating disorders (Darcy et al., 2012; Fitzpatrick et al., 2012) and obesity (Perpina et al., 2017) showed worse cognitive flexibility and set-shifting than adolescents with normal weight. Accordingly, the association highlighted by this study could confirm an early relationship between these two variables.

It is well-known that EFs improve with age and the continuing development of neural connectivity in the frontal lobe until adulthood (Kalkut et al., 2009). Adolescence seems characterized by a strong upgrading of set-shifting compared to children; accordingly, the results of this study could be interpreted in two different ways. On the one hand, considering the EFs as possible predictors of excessive body weight, the lower improvement of shifting in adolescents could be associated with a maladaptive food approach. It would be characterized by overeating and associated with overweight, which might develop over time to obesity. However, to confirm this hypothesis, further studies would detect the eating behavior associated with being overweight. On the other hand, starting with overweight, adiposity may begin to affect executive performance through damaging the prefrontal areas involved in their functioning (Favieri et al., 2019; Yang et al., 2019). However, we should try to understand why the other executive functions are not affected in this case.

The results in young adults should be interpreted in line with these latter assumptions. Again, in this group, one EF, i.e., motor inhibition, more than the others, seems to be involved in body weight, as underlined by the regression analysis. As previously reported, alteration in motor inhibition would explain the overeating behavior associated with overweight. As in the case of adolescents, the double interpretation can be considered.

In line with the present findings, we can finally declare that the bidirectional relationship that emerged during the life span between weight status and EFs showed different patterns in different ages. We hypothesize that these different patterns would express a first causal directionality of the relationship during the first phases of the development. The alteration in the normal development of EFs, specifically in adolescence and first adulthood, could influence the weight changes via the approach to food and eating behavior, but in different ways. While the adolescents would express higher difficulty in shifting the behavior from maladaptive (i.e., overeating behavior) to adaptive (i.e., healthy eating behavior) due to alteration in cognitive flexibility (Diamond, 2013), the young adults could be characterized by a worse motor inhibition, that the action of overeating could be expressed in response to appetible food stimuli (Favieri et al., 2020; Wessel, 2017). This interpretation agrees with executive control ability to moderate healthy eating behavior (Hall et al., 2008). However, further studies on these aspects are needed.

A last interesting result is the different relationship pattern between executive functioning and hunger sense in different ages. Only in adolescence, higher levels of hunger are associated with worse performance in the Go/No-Go Task and the 1-back task. Especially the result on the motor inhibition is in line with previous results showing in adolescents a higher feeling of hunger associated with lower inhibition responses (Nederkoorn et al., 2009; Moreno-Pedilla et al., 2018), while no relation was reported in both children (Nederkorn et al., 2015) and young adults (Jesinka et al., 2012). Further studies should consider the feeling of hunger as a possible moderator in the relationship between executive functioning and weight gain.

Although these results should be considered preliminary, they furnished useful information about a relationship still not clear. However, some limitations should be highlighted. First, the adoption of the BMI represents a limit for its low power in identifying the health risk factors associated with overweight and its low generalizability, especially in children and adolescents. However, it is necessary to define better which index should be adopted to identify early the risk associated with excessive body weight. The impact of age in this measure represents another limit, although its influence was controlled through statistical strategies. Another limitation is represented by the small sample size and the absence of middle adults and late adults. Overcoming this limitation would allow for clearer and more representative results. A last but important limitation is the absence of certain psychological (e.g., impulsivity trait, emotional regulation) and physiological variables (e.g., glucose levels) and the lack of information about eating behaviors and lifestyle habits that can directly or indirectly influence the relationship between EFs and overeating.

Conclusions

Executive functions significantly predict high fat intake (e.g., Hall & Fong, 2013). The different components of EFs appear to be predictive of distinct weight conditions (Hall et al., 2008). This study would seem to confirm the association between overweight and executive functions. However, it also defines different association patterns in various phases of development that could represent the prodromes of an exacerbation of the condition, up to severe cases of morbid obesity over time.

According to the high prevalence rate and the direct and indirect health care costs of excessive body weight, the World Health Organization focused attention on defining prevention programs to reduce its risk of overweight occurrence (WHO, 2020). However, the programs implemented so far have not been sufficiently effective.

In line with our results, early prevention interventions involving children and adolescents are the most reasonable response to reduce the risk of obesity. Considering the role of EFs in modulating and controlling goal-directed behaviors, including those associated with body weight gain, these interventions will need to consider executive functions and their different evolution during development.

CHAPTER 4. High Executive Functions and Overweight: the role of Decision Making and Planning in healthy individuals with excessive body weight

Introduction

Overweight and obesity represent a modern global epidemic and a major public health concern associated with increased mortality and reduced quality of life and life expectancy (Brockmeyer et al., 2017). Excessive weight gain represents a risk factor for many chronic conditions (e.g., hypertension, Jiang et al., 2016; diabetes, Hauner, 2017; cardiovascular disorders, Littleton, 2012), and it is related to a series of psychopathological disorders (as anxiety and depression; Carey et al., 2014; Gariepy et al., 2010), cognitive dysfunctions (Favieri et al., 2019), and a general impairment of well-being and quality of life (Kolotkin et al., 2001). The prevalence of obesity has substantially increased worldwide over the last decades (Rotge et al., 2017; World Health Organization, 2020). In the world, more than 600 million adults (38% of the global population) and about 42 million children and adolescents (17% of the total) are affected by overweight or obesity (Gettens & Gorin, 2015; Ogden et al., 2014; Yumuk et al., 2015), and Italy reports one of the highest rates of overweight of European countries (14% of the overall population; Rechel et al., 2018; WHO Regional Office for Europe, 2016). Maladaptive eating behavior represents the main cause of body weight increase, and it appears to be influenced by many psychological (e.g., mood, impulsivity) and environmental (e.g., food availability, social pressure) conditions.

Many evidence reported an association between impairments in executive functions and excessive body weight during life span (for a review: Favieri et al., 2019; Fitzpatrick et al., 2013), especially in the population with obesity or severe obesity (i.e., Body mass index (BMI) above 30 Kg/m^2). Although a causal relationship between the variables was not confirmed and some inconsistencies due to methodological differences (e.g., samples characteristics, research procedure, outcomes, tools) was reported, many studies cross-sectionally underline lower performances in executive functioning tasks in the condition of obesity compared to normal-weight healthy status (Rotge et al., 2017; Favieri et al., 2019). Moreover, the studies reported a longitudinal relationship between weight gain and cognitive impairment and an association between low performances in executive tasks and weight loss failure (Stinson et al., 2018; Galioto et al., 2016; Steenbergen and Colzato, 2017). Despite it may represent a key to understanding the genesis of the link (Favieri et al., 2019), the literature which detected the relationship between executive functions and minor overweight (i.e., BMI between 25 and 30 kg/m^2) is poor and reports discrepancies,

Our previous study (Favieri et al., 2021), aimed to analyze the association between executive functions and overweight in the healthy population and reported interesting results about the age-related differences in executive patterns associated with body weight. The study, focusing on Diamond's tripartite executive functions model (i.e., inhibition, updating, shifting; Diamond, 2013), confirmed in young adults an association between cognitive inhibition and weight status, i.e., worse performances in cognitive inhibition were associated with an increased BMI, allowing to hypothesize a possible predictive role of this function in the increase of body weight.

Executive functioning represents an umbrella term encompassing different cognitive domains regulating goal-directed behavior (Gilbert and Burgess, 2008). Diamond’s model simplified the complex organization of the executive domain, which included higher levels of functions hard to differentiate, such as attention, planning, problem-solving, decision-making (Fitzpatrick et al., 2013). Generally, the studies on obesity mainly involved simpler executive functions (e.g., working memory, inhibition, set-shifting; Favieri et al., 2019). However, a portion of the literature has investigated the relationship between obesity and more complex executive functions such as decision making and planning (e.g., Goldschmidt et al., 2018; Stinson et al., 2018; Perpina et al., 2017).

A recent meta-analysis of Rotdge and colleagues (2017) focused on the analysis of decision-making in obesity through the Iowa Gambling Task (IGT; Bechara et al., 1994) as a gold standard procedure for assessing decision-making abilities in ambiguity conditions (i.e., without knowledge of different options). The study reported that obesity was associated with a deficit in making a decision under uncertain conditions (Rotdge et al., 2017), and low decision-making was associated with failure in weight loss programs. Lower performances in decision-making tasks in individuals with obesity (e.g., Brogan et al., 2011; Fagundo et al., 2012; Pignatti et al., 2006) could be associated with a difficulty in making appropriate decisions in daily life, expressed by overeating behaviors causing inadequate weight. However, the few studies on overweight condition (BMI< 30 kg/m^2) did not confirm this result (Navas et al., 2016; Stinson et al., 2018), indicating a possible different pattern in less severe condition of body weight.

This study aimed to provide new evidence in the analysis of the relationship between executive functions and body weight, deepening the analysis of more complex executive functions less investigated (i.e., decision making) or never approached (i.e., planning) in overweight conditions. In particular, the association between body weight and decision making and planning performances in a healthy population of adults and young adults, i.e., without eating disorders, medical or psychopathological condition, and without severe obesity (BMI> 35 kg/m^2) was investigated. According to the previous systematic review (Favieri et al., 2019) and with the aim to detect possible age-related differences in the relationship between weight condition and higher-level executive functions, young adults (between 18 and 30 years) and middle adults (between 30 and 64 years) were considered separately. It was expected lower performances in decision making under risk (Iowa Gambling Task; Bechara, 1998) in the condition of overweight compared to normal weight, according to previous results reporting this association in adults with obesity (e.g., Navas et al., 2016; Borgan et al., 2011; Danner et al., 2012). Moreover, although the literature is very weak and inconsistent about the relationship between planning and excessive body weight, according to the hypothesis of a general executive impairment related to overweight (Favieri et al., 2019), we expected lower planning functioning associated with the overweight condition (Qavam et al., 2015). It was expected a role of age in this relationship. It is expected a more impaired executive functioning in middle adults than young adults, for the principle of bidirectionality that emerges between executive functions and overweight

(Favieri et al., 2019) over time and that could lead to aggravation of cognitive deficits in the case of reiteration of maladaptive behaviors associated with the weight gain.

Methods

Participants

One-hundred and forty-five participants (50 males and 96 females; mean age: 36.01 years SD = 16.44) voluntarily took part in the study. Specifically, 85 participants were young adults attending "Sapienza" University of Rome (age range: 19-29 years; 29 males, 56 females; mean age: 23.25 years SD= 2.54), and 59 participants were adults recruited in Roman territory (age range: 30-64 years; 21 males, 39 females; mean age: 54.08 years SD= 9.16). Of the overall sample, 66 participants (32 males; 36 females) reported a BMI beyond the 25 Kg/m^2 as an index of overweight (46 percent of the sample). Table 1 and Table 2 showed the main characteristics of the sample.

The participants were included in the study if they did not present eating disorders diagnosis or food allergies, severe obesity condition, chronic medical diseases, or any psychopathological conditions (e.g., anxiety, depression). Moreover, a normal or corrected-to-normal vision and was requested.

Table 1. Characteristics of the sample classified according to age range and body weight condition

	Young Adults		**Middle Adults**			
	Normal weight	**Overweight**	**Normal weight**	**Overweight**	**F**	**p**
N (m/f)	50 (14/36)	35 (15/20)	27 (4/23)	33 (17/16)		
Age (mean, sd)	22.52 (2.23)	24.28 (2.63)	54.37 (9.27)	53.85 (9.20)	1.17	0.28
Years of Education (mean, sd)	15.94 (1.63)	16.43 (1.96)	12.96 (4.49)	12.97 (3.17)	< 1	0.61
Physiological Measures (mean, sd)						
Weight (kg)	59.77 (8.80)	78.77 (11.06)	58.33 (6.24)	83.44 (12.41)	3.22	0.07
Hight (m)	1.68 (0.08)	1.71 (0.10)	1.62 (0.07)	1.71 (0.10)	3.60	0.06
BMI	21.05 (2.06)	26.79 (2.09)	22.21 (1.59)	28.36 (2.58)	< 1	0.57
Weist-to-height ratio	0.44 (0.04)	0.50 (0.05)	0.47 (0.04)	0.56 (0.05)	1.78	0.19
Body Adiposity Index	25.50 (4.18)	31.81 (5.99)	27.60 (1.98)	28.27 (3.02)	6.09	0.01*
Systolic Blood Pressure	116.49 (10.45)	119.89 (11.29)	117.97 (14.17)	124.25 (15.22)	< 1	0.53
Dyastolic Blood Pressure	72.18 (8.02)	73.64 (7.52)	75.78 (9.08)	80.50 (9.62)	1.11	0.30

Table 2. Demographic and Lifestyle characteristics of the sample

	N (%)
Demographic Information	
Sex	
Males	50 (34)
Females	96 (66)
Education	
Low/Middle School Degree	17 (32)
High School Degree	67 (46)
Undergraduate/Graduate Degree	61 (42)
Occupational Status (n, %)	
Occupate	47 (32)
Inoccupate	23 (16)
Students	75 (52)
Marital Status (n, %)	
Single	89 (61)
Married	44 (30)
Divorced/Separate	12 (8)
Lifestyles Habits	
Smoking Habits	
Yes	49 (66)
No	96 (44)
Caffeine Consumption	
Yes	115 (79)
No	30 (21)
Alcohol Consumption	
Yes	70 (48)
No	75 (52)
Physical Activity	
Yes	39 (27)
No	106 (73)

Outcomes

Demographic and clinical information

A semi-structured interview was adopted to collect the main demographic information of each participant (gender, age, level of education, marital status, occupation) and medical and clinical history.

Executive functions

- *Decision Making*

Decision-making was assessed using a computerized version of the *Iowa Gambling Task* (IGT; Bechara et al., 1999), completely superimposable on the original version.

Apparatus: the task was administered via E-Prime 2.1 software (Psychology Software Tools Inc., Pittsburgh, PA, USA) on a personal computer, equipped with a 15-inch monitor. The responses were enabled by four keys of the computer keyboard.

Stimuli: Four decks of cards ("A", "B", "C", and "D") with a red cover in the back and a Joker of Spades in the front constituted the stimuli, on a green background (Bechara et al., 2000).

Procedure: ***e***ach card in the decks is associated with a win or a loss. The decks differed in the frequency and number of wins and losses. Decks A and B were considered disadvantageous, with large short-term

wins ($100) but long-term losses. Deck A was associated with more frequent loss but less plentiful than in deck B. Overall, decks A and B led to a loss of $250 for every 10 cards drawn. Decks C and D were more advantageous although characterized by a small short-term payout ($50 each). The two decks differed in the frequency and magnitude of the loss. Deck C had more frequent but lower losses, than deck D. Every 10 cards drawn on these decks resulted in a win of $500 with a loss of $250. The amount of money won (written in green) and lost (written in red) was shown for each trial, and during the overall task duration, the total budget was indicated. Each participant started with a $2000 credit and was informed some decks were more advantageous than others.
The participant should press one of the four keys in the keyboard, corresponding to the deck they intended to choose. The test ended automatically after the hundredth selection (100 trials). The locations of the losses in this experiment were adopted by Bechara et al. (1999). The *learning of long-term consequences (LTC)* and the *bias of infrequent loss (IFL)* indices were calculated within each 20-trials block. The LCT was calculated by subtracting the number of disadvantageous choices from the number of advantageous choices ((C+D)-(A+B)). The IFL was calculated by subtracting the frequent-loss deck choices from the infrequent-loss deck choices ((A+D)-(B+C)). Higher scores in both the indices indicated better decision-making function.
An example of the IGT procedure was shown in Figure 1.

Figure 1. Example of IGT procedure.

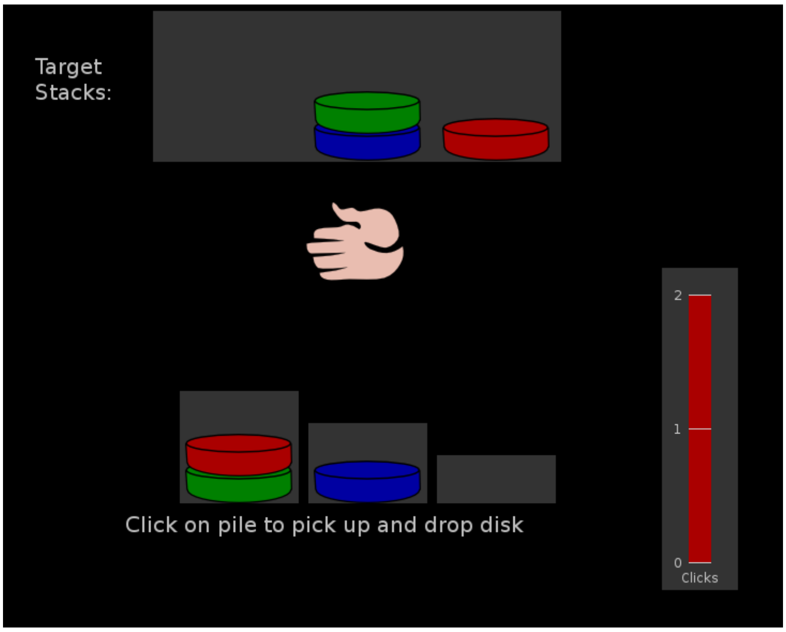
- *Planning*

Planning abilities were assessed by a computerized version of the Tower of London task (Shallice, 1982; Muller, 2014).
Apparatus: the task was administered via Pebl 2.1 software (Muller, 2011 Computer software retrieved from http://pebls.sf.net.) on a personal computer, equipped with a 15-inch monitor. The responses were enabled through the mouse control.

Stimuli: on the top of the screen, three colored discs (blue, green, red) were located on a structure with three vertical sticks in a predefined order. At the bottom of the screen, the same frame was presented but with movable discs.

Procedure: the participant must order the discs one by one to recreate the configuration shown in the 12 trials. The whole sequence of moves must be carried out mentally before executing the sequence. For each trial, only a predetermined number of movements can be made, and the number of available movements was shown on a vertical bar at the side of the screen. A total score was calculated by Pebl program, considering the number of trials correctly completed in the minimum possible moves. A lower total score indicated lower planning performances. An example of the TOL procedure was shown in Figure 2.

Figure 2. Example of procedure of TOL.



Apparatus

A digital balance was used to assess the weight of each participant (Kg), and a wall-mounted anthropometer was adopted to measure the height (m). The BMI was calculated by dividing weight by height (in meters squared). The WHO criteria were adopted to classify the BMI (WHO, 2020). Waist and hip circumferences were measured by a tape measure. The waist-to-height ratio (W/Hr; Maffeis et al., 2008) and body adiposity index (BAI = ((hip circumference)/((height)$^{1.5}$)–18)); Bergman et al., 2011) were calculated as alternative indices of body weight. A digital sphygmomanometer was used to measure the participants' systolic and diastolic blood pressure, considered control variables.

General Procedure

The written informed consent was signed before the evaluation by each. The research was conducted according to the Helsinki Declaration and it was approved by the Local Ethics Committee (Department of

Dynamic and Clinical Psychology—"Sapienza" the University of Rome). Each participant was individually tested in a silent, dimly illuminated room with a comfortable temperature. Before the experimental session, where the IGT and TOL were randomly administered, the aims of the study were explained to the participant, and the semi-structured interview was administered.

Data analysis

The descriptive analyses were calculated, considering the groups of age (young adults and middle adults) and the weight condition (normal weight, overweight) and univariate analyses of variance (ANOVAs) were carried out to control the differences between groups in age, years of education and physiological measures collected during the assessment.

Linear Pearson's r correlations were calculated to verify the general association between EFs (TOL score, mean of LTC and mean of IFL) and weight condition (BMI, Body Adiposity Index and Waist-to-heigh ratio)

Subsequently, mixed ANOVAs were carried out to assess the differences between the groups, considering age and body weight condition, in the LTC and IFL indices of the five blocks of the IGT. To assess the planning performances in the groups, an ANOVA on the total score of the TOL was carried out.

Results

Pearson's r correlations did not show significant association between EFs and weight status' variables.

Table 2. Correlational analysis

	TOL_Total Score	LTC	IFL
BMI	-0.08	-0.04	-0.06
	p=0.40	p=0.73	p=0.54
Waist-to-heigh Ratio	-0.11	-0.003	-0.11
	p=0.28	p=0.97	p=0.27
Body Adiposity Index	-0.12	-0.11	-0.07
	p=0.23	p=0.27	p=0.45

The statistical analyses on the performances in the executive tasks (IGT and TOL) did not report significant differences between the groups considering both age group and weight condition.

Table 3. Means and Standard Deviations of the groups in the IGT and TOL tasks.

	Young Adults		Adults			
	Normal weight	**Overweight**	**Normal weight**	**Overweight**	**F**	**p**
IGT						
Learning of long-term consequences (LTC)						
Block 1 (from 1 to 20 cards)	-3.24 (5.43)	-3.81 (5.43)	-5.47 (5.88)	-2.77 (4.31)	2.46	0.12
Block 2 (from 21 to 40 cards)	-0.12 (4.97)	-0.12 (4.95)	0.53 (6.57)	-1.15 (5.58)	< 1	0.42
Block 3 (from 41 to 60 cards)	1.20 (7.74)	0.87 (6.30)	2.67 (6.66)	-0.46 (6.87)	1.00	0.32
Block 4 (from 61 to 80 cards)	1.68 (6.74)	2.41 (6.94)	-0.80 (7.40)	2.31 (7.93)	< 1	0.40
Block 5 (from 81 to 100 cards)	2.44 (9.24)	2.53 (6.91)	2.93 (6.67)	0.61 (7.17)	< 1	0.45
Global IGT Score	1.96 (25.74)	2.00 (18.26)	-0.13 (22.61)	-1.46 (19.25)	< 1	0.88
Bias of Infrequent Loss (IFL)						
Block 1 (from 1 to 20 cards)	-0.24 (4.36)	-1.12 (3.04)	1.60 (3.79)	-0.23 (4.78)	< 1	0.56
Block 2 (from 21 to 40 cards)	-1.16 (4.80)	-0.06 (4.23)	2.53 (5.42)	0.38 (4.04)	3.20	0.08
Block 3 (from 41 to 60 cards)	-0.12 (6.38)	0.81 (5.65)	0.40 (4.42)	-1.31 (4.86)	1.28	0.26
Block 4 (from 61 to 80 cards)	0.60 (5.83)	0.60 (5.94)	2.00 (6.05)	-1.08 (7.42)	1.54	0.22
Block 5 (from 81 to 100 cards)	-0,28 (7.74)	0.72 (5.24)	-2.53 (4.50)	-2.46 (7.38)	< 1	0.73
TOL						
Total Score	24.06 (6.87)	22.45 (7.80)	19.93 (4.12)	21.56 (6.41)	1.61	0.21

Specifically, considering the LTC index of the IGT, the ANOVA showed only a significant effect of the block number ($F_{4,564}$= 18.68; p= 0.0001; pη^2= 0. 14), characterized by a significant increase of LTC from the first block to the others (first vs second: t= -5.46; p= 0.0001; first vs third: t= -6.45; p= 0.0001; first vs forth: t= -6.34; p= 0.0001; first vs fifth: t= -6.44; p= 0.0001) in the general sample, according to the literature. Moreover, starting to the third block no significant increase of the score was reported (third vs forth: t< 1; p= 0.67; third vs fifth: t= -1.32; p= 0.19; forth vs fifth: t< 1; p= 0.34), indicating a stabilization of the LTC pattern.

Considering the IFL index of the IGT no main effect of the task ($F_{4,564}$= 2.00; p= 0.10; pη^2= 0. 02), age (F< 1; p= 0.95) and weight condition (F< 1; p= 0.37) were reported. Moreover, no interaction effect was highlighted, except considering the block x age group interaction ($F_{4,564}$= 4.06; p= 0.003; pη^2= 0. 03). Young adults reported a higher bias of infrequent loss compared to middle adults in second (mean difference: -2.07; t= -2.28; 0.02) and fifth block of the IGT (mean difference: -2.72; t= -2.03; p= 0.04). No other significant differences between groups were reported (F< 1; p> 0.50).

The ANOVA on the Global score of the TOL did not show significant differences between groups neither considering the main effect of age group ($F_{1,141}$= 3.87; p= 0.06; pη^2= 0.01) and weight condition ($F_{1,141}$< 1;

p= 0.99; $p\eta^2$= 0.01) nor considering the interaction age group x weight condition ($F_{1,141}$= 1.61; p= 0.21; $p\eta^2$= 0.01). See table 3.

Discussion

Previous studies have confirmed an association between executive functions and both maladaptive eating behavior (Dohle et al., 2018) and excessive body weight (Yang et al., 2018; Favieri et al., 2019). However, a large portion of them focused on basic executive functions (i.e., inhibition, working memory, shifting), while the association between more complex executive functions (i.e., problem-solving, decision-making, planning) and weight status is poorly analyzed. Moreover, the research on this topic focused on obesity condition, underestimating the importance of underlining an association in the earliest stages of overweight. This study was one of the first that analyzed the relationship between weight status in healthy individuals and complex executive functioning, focusing on planning and decision-making. The present study assumed that planning and decision-making, involving different cognitive mechanisms and neural substrates aimed to control goal-directed behaviors, could affect weight gain.

Decision-making covered some aspects of reward sensitivity (Brockmeyer et al., 2017) and the assignment of values and probabilities to behavioral patterns aimed at a specific outcome. In line with Damasio's somatic marker hypothesis (1994), some authors hypothesized a possible association between decision-making alterations and eating behaviors associated with obesity. This relationship was ascribed to the hypersensitivity to immediate reward, the failure to generate appropriate responses to certain organic signs (e.g., gut activity) (Verbaken et al., 2014), or the presence of impulse-control problems (Favieri et al., 2019; Rotdge et al., 2017). The results of this study did not confirm an association between decision-making and the first stages of overweight in a sample of young adults (age range: 18-29) and middle adults (age range (30-64). These results agree with the few studies that have analyzed this relation in the healthy overweight population of adults (Navas et al., 2016; Stinson et al., 2018). The theoretical models which lead back the obesity due to overeating at an alteration of decision-making (Davis et al., 2007) were not confirmed in less severe overweight condition. However, further studies are needed to reinforce these results.

Similar results were reported about planning, a high executive function useful to organizing and control complex behaviors (e.g., eating habits; Favieri et al., 2019). The planning was poorly investigated in association with excessive body weight (Qavam et al., 2015; Sweat et al., 2017), with inconsistent results. Quavam and colleagues (2015), analyzing a group of adolescents (age range: 15-18 years), found worse performances in the TOL task, a measure of planning and problem solving, in people with overweight and obesity than normal weight. However, the authors did not clearly specify if people with overweight and obesity showed a different pattern. On the contrary, Sweat et al. (2017) did not highlight a difference between young adults with obesity and normal weight in planning abilities assessed by the TOL. To our knowledge, no other studies analyzed planning performances in overweight condition. According to Sweat and colleagues (2017), our study did not observe significant differences in TOL performances as a function of weight status. However, although not statistically significant, different patterns emerged between young and middle adults considering mean trends. A possible association between overweight and planning impairment was suggested by lower means score in overweight than normal weight in young adults. The few studies on planning do not allow us to make further inferences about this finding, but our results suggest a possible involvement of higher-level executive functions in overweight.

Generally, the results of this study should be interpreted considering different aspects. Differently from simple executive functions that could represent a marker of the risk of weight gain (as supported by our previous study), the more complex and integrated executive functions may come into play in more severe phases of overweight, and they could be characterized by a bidirectional relationship with overweight (Favieri et al., 2019). We can hypothesize that some executive functions (e.g., shifting, inhibition, Favieri et al., 2021) can represent risk factors for establishing maladaptive behaviors that lead to increased weight. An association between these executive functions and body weight would emerge in the early stage of development (Favieri et al., 2019) and less severe overweight conditions (Favieri et al., 2021). Instead, other executive functions, specifically those characterized by greater integration of neural networks (e.g., planning and decision-making), could be not predictors of weight gain, but rather the outcome of the physiological alterations associated with excessive adipose accumulation (e.g., chronic inflammation, alterations in cerebral blood profusion; Lasselin et al., 2016; Quavam et al., 2015). Obesity appears related to many brain changes that potentially impact cognitive and executive functions (Gunstad et al., 2007), and the worsening will lead to an exacerbation of inappropriate behaviors causing obesity. This hypothesis can be supported by the absence of differences in our sample between young adults and middle adults. Considering aging, we expected an age-related difference in the relationship between executive functions and overweight, according to the persistence of a condition of excessive body weight over time, which could have affected executive functions. This pattern was not confirmed. This result would indicate that less severe overweight is not associated with physiological alterations capable of determining executive impairment, especially considering more complex EFs, over the life span. This assumption should be interpreted with caution, for the cross-sectional design adopted by the study, which does not give us information about the evolution and changes in weight over time. However, it could indicate that overweight is not as severe as obesity, neither in its symptoms nor in its possible impact on cognitive functions over time.

Although the preliminary results of this study allowed interesting considerations, some limitations should be highlighted. First, the sample size was relatively small, especially considering the overweight condition, and it may have limited the effect size of the study, which may have prevented significant differences. Another limit is represented by the cross-sectional design. A longitudinal study would allow for highlighting a possible trend of the relationship over time. Another limitation is related to the poor theoretical background of the study, specifically considering planning that could have precluded the possibility to develop new inferences about the construct associated with weight condition. A further suggestion could be to consider in future studies cognitive tasks involving food cues with the aim to identify a possible involvement of high executive functions in response to food cues, rather than a general impairment, in the case of moderate overweight.

Conclusions

Investigating the aspects that could influence eating behavior and body weight changes appears relevant, considering the role of obesity as a current public health concern. Knowing the role of some specific executive functions in driving complex behaviors, such as eating behavior, can encourage considering the body weight changes in a new perspective that allows including cognitive variables in weight gain prevention programs. Potentially, these variables could influence the approach towards food, influencing body condition. Although the scarce investigations on this topic, studies on weight loss interventions emphasized the potential influences of executive functions on the success of these programs. Understanding which executive functions are involved in overweight and how their involvement over time modulates the eating behavior will allow new treatment approaches integrating weight loss programs and executive function training (Favieri et al., 2019). Moreover, it can help us develop an integrated and more suitable theoretical model on the relationship between executive functions and excessive body weight.

General Conclusions

Throughout this thesis, many times has been highlighted the high prevalence of obesity in the world: 38 percent of the general adult population, 17 percent of children and adolescents, about 14 percent of the European population, and 35 percent of the Italian population (data come from Gettens & Gorin, 2017; Yumuk et al., 2015; Rechel et al., 2018). These data may not make clear the impact of the worldwide obesity epidemic; however, they were associated with a global alert toward the association between obesity and general wellbeing and health of individuals, which prompted the welfare and public health institutions (e.g., WHO, CDC, ISS) to develop suitable strategies to address this serious problem (WHO, 2020). Overweight is increasing, with prospective studies indicating 2030 as a critical point of maximum spread of this epidemic. It is well established that obesity represents a risk factor for many medical conditions (Jiang et al., 2016; Hauner, 2017; Littleton, 2012), psychopathological disorders (Carey et al., 2014; Gariepy et al., 2010), and cognitive dysfunctions (Favieri et al., 2019). Therefore, defining the best tools and practices to fight it in the early stages of onset is the best key to reversing the negative trend, stratified in all cultures and all social and age groups.

Deeping the possible risk or maintaining factors related to overweight is relevant to understand the variables mainly associated with the overweight condition. Many studies have focused on the relationship between body weight and cognitive processes, including executive ones. Accordingly, a systematic review investigated the relationship between excessive body weight (i.e., overweight and obesity) and executive functions. The results confirmed this relationship, suggesting a bidirectional trend that could cause the high failure rate of weight reduction interventions. The conclusions of the first chapter indicated the lack of decisive responses by the previous literature, specifically in determining causality and features of the relationship. However, the complex interaction between different factors that influence people's attitude to food and eating, as primary causes of weight gain and executive functioning, emerged. One of the aspects highlighted by the review, i.e., the low number of research focused on the first overweight stages, has driven the studies presented in the other chapters of the thesis. This lack of studies could be due to some difficulties determined by adopting indirect body fat measures, such as the BMI. BMI limits defining the risk associated with a slight and moderate overweight (BMI< 31) because it does not permit distinguishing muscular and fat masses. Another limit is due to cultural aspects of Western society that tends to underestimate the risk of moderate overweight, postponing it to situations of severe obesity when the bidirectional nature of the damage is already established.

The first experimental study (Chapter 2) showed a possible role of the executive response toward food stimuli in weight gain. This study was the first to examine contemporarily different versions of tasks assessing executive functions and including food stimuli. It has contributed to identifying an association between the weight condition and the executive functions, which also involves environmental stimuli associated with eating behavior. These preliminary results may have clinical implications for preventing more severe overweight conditions in which the overeating conditions could be more influenced by prolonged exposure to high palatable but hypercaloric stimuli. Moreover, according to one aim of the thesis, the results indicate the importance of investigating these aspects to reduce obesity onset in the general population.

The second study (Chapter 3) aimed to detect the involvement of the executive functions and their predictive role on BMI changes in a sample of healthy individuals from childhood to young adulthood. Results have highlighted an association between high BMI and worse executive functions in adolescence (i.e., shifting) and young adulthood (i.e., inhibition), but not in childhood. The conclusions of the study allowed us to assume that alterations in the normal development of EFs could influence weight changes via the approach to food and eating behavior, with diverse patterns in the different stages of development. Various executive patterns in the distinct development phases could represent the prodromes of an exacerbation of the overweight condition. In line with the results, early prevention interventions are the most reasonable response to reducing obesity during lifespan.

The final study (Chapter 4) aimed to provide new evidence characterizing the relationship between executive functions and body weight, deepening the analysis of more complex executive functions (i.e., decision-making and planning) in overweight conditions in a healthy population of middle adults and young adults. Differently from the results on low-level executive functions (i.e., working memory, inhibition, shifting), no association was observed between high executive functioning (decision-making and planning) and weight status in the considered sample. However, despite the poor theoretical background, the study allowed us to hypothesize a novelty pattern between executive functions and weight. The lack of an association between the variables has allowed us to hypothesize that, if some executive functions should be considered already in the non-pathological phases of overweight, more complex executive functions could come into play in the following phases of overweight, indicating that we should reduce the attentional focus on specific functions in the early stages of overweight.

In conclusion, despite the limitations arising from having put in place preliminary studies, with the biggest limitation of the small sample size and the low percentage of critical BMIs above the threshold of normal weight, we have highlighted the need to approach executive functions in the context of overweight and the related overeating behavior associated with it.

During the data collection process of this thesis, like so many other researchers, we had to deal with a pandemic that bypassed in magnitude, severity, and emergency, the obesity epidemic. The COVID-19 pandemic has limited the possibility of deepening some aspects of the present research; besides having impacted the quality of the study, it has had consequences on the lifestyles of the world's population, involving, among other things, eating habits. For these reasons, this thesis is not too far away from what will be the future legacy of the pandemic. A growing number of studies highlighted which dietary habits changed during COVID-19, reported an unhealthy diet pattern (with a higher snack and hypercaloric food consumption) associated with weight gain and reduction in physical activity (e.g., Alhusseini & Algahtani, 2020; Sidor & Rzymski, 2020; Pellegrini et al., 2020) in the general population.

Nutrition and weight are public health conditions that cannot be ignored, even in this exceptional situation, for their implication as additional health risk factors (i.e., reduction of immune system's response, an increase of inflammatory response; Alhusseini & Algahtani, 2020) that will increase further if the maladaptive eating behavior consolidates. Therefore, the findings of this research should be taken up and deepened in future studies to intervene in the inevitable consequences of excessive body weight.

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