



Food craving predicts the consumption of highly palatable food but not bland food

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Abstract

The impact of obesity on physical and psychological health is well recognized in the literature with, among others, evidence of alterations in cognition. Indeed, obese populations are characterized by lower executive functions as well as an enhanced food craving. However, the relationship between executive functions and food craving remains unexplored. Moreover, these two variables have also been shown to predict food intake, but studies in the context of obesity are lacking. Thus, this study had two objectives: (1) determining if executive functions and food craving are linked, and (2) examining the predictors of highly palatable food intake and bland food intake. First, it was hypothesized that executive functions would be negatively associated with food craving. Second, it was expected that food craving would predict positively highly palatable food intake but not bland food intake. Third, it was predicted that executive functions would predict negatively highly palatable food intake and positively bland food intake. 48 participants (34 females) with BMIs ranging from 17.9 to 46.4 took part in two experimental sessions. First, executive functions were assessed using the delayed discounting task (impulsivity towards food and money) and the color–word interference test (CWIT; inhibition/flexibility). Second, a cue-induced food craving protocol, with images as well as real food, was administered followed by an ad libitum food intake protocol including both highly palatable and bland food. The inhibition/flexibility condition of the CWIT was significantly and negatively correlated with food craving following induction. Highly palatable food intake was significantly predicted by food craving following induction, but bland food intake was not. This study reveals an association between lower inhibition/flexibility and susceptibility to food craving induction that is of great importance in obesogenic environments. Moreover, this study confirmed the link between food craving and food intake, and showed for the first time a specific contribution of food craving to highly palatable food intake but not to bland food intake, highlighting its potential influence in obesity. This work leads to future research questions regarding the possible benefits of cognitive remediation interventions, as well as interventions aiming at reducing food craving, in weight loss programs.

Level of evidence Level IV, quasi-experimental study.

Keywords Food craving · Executive functions · Color–word interference test · Food intake · Obesity

Introduction

Obesity is an epidemic health condition for which the prevalence has doubled over the last 40 years [1] with one in four adults being obese in Canada in 2016–2017 [2] and more than one in three adults being obese in the United States in 2015–2016 [3]. Its impact on physical and psychological health is now well recognized [4, 5]; obesity is a public health concern. While obesity seems to be primarily a physical condition, it is now known to be associated with a number of psychiatric and neurological symptoms as well. In the cognitive domain, growing evidence point to an imbalance between the cognitive control and the reward

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systems in response to food cues in obese populations [6–8]. Behaviorally, this pattern is thought to lead to an enhanced motivational drive towards food (mainly high-calorie foods), namely food craving, and a reduced behavioral control over food intake through poor executive functions [6]. On one hand, the understanding of these mechanisms is of clinical interest as they can interfere in the treatment of obesity, and on the other hand, a better description of the mechanisms involved can foster the development of new treatments.

Food craving, defined as an intense desire to consume a specific food or food type that is difficult to resist [9], is now known to be linked to obesity. Indeed, a higher BMI is associated with frequent food cravings [9] and food cravings are associated with weight gain over time [see 10 for a review]. Food craving is a complex concept and many types have been documented in the literature. Hallam et al. [11] have described a food craving model explaining the different types including the moment at which craving occurs with “now” referring to state food craving, and “general” referring to trait food craving. The presence or the absence of an external trigger is also included in the model leading to cue-induced craving and tonic craving, respectively. Regarding cue-induced food craving, studies of its impact on food intake are sparse with only one study in obese adults [12], and one study in overweight adults [13].

Regarding executive functions, there is extensive literature in obese populations showing that their performance is lower than the one of people with healthy weight [14–18]. Cognitive inhibition, cognitive flexibility, working memory, verbal fluency, and decision making, among other cognitive functions, have been shown to be reduced in obesity [16–24]. These deficits of varying intensity are of clinical interest, as they have been associated with different eating behaviors [24–27] and clinical outcomes such as success in a weight loss intervention [28–30]. Even though neuroimaging data have shown an imbalance between the reward system and the cognitive control system in obesity [8], at the behavioral level, the interaction between food craving and executive functions has not been investigated so far. Based on the neuroimaging findings, one could hypothesize that a negative relationship might exist between these two variables. Indeed, the activation of the cerebral networks underpinning food craving and executive functions is opposite while seeing food images [8].

For its part, food intake is known to be influenced by a multitude of factors [31], and food craving and executive functions are among them [9, 24]. Indeed, food craving has been found to enhance food intake in healthy weight, overweight, and obese populations [9, 32–34]. Moreover, most craved foods have a high energy density and are high in fat and carbohydrates [35]. There is also evidence of a specific contribution of the type of food craved to the intake of these foods [9, 34, 36]. However, the influence of food craving in

the context of a food choice, when both highly palatable food and bland food are offered, has not directly been investigated in an experimental study. Based on previous literature, one could hypothesize that food craving would predict highly palatable food intake, but not bland food intake. Besides, executive functions also have an influence on food intake. Indeed, inhibition predicted less high-fat food consumption and snack food intake in general population samples [24, 25], and better switching and flexibility abilities predicted greater fruits and vegetables intake, as well as less high-calories snack food in a sample of students [25]. However, very few studies have investigated the impact of BMI on the relationship between executive functions and food intake. Indeed, only one study investigated the link between executive functions and food intake in obese adults, finding that perseverative errors in the Wisconsin Card Sorting Test were positively correlated to food intake [26].

This study had two objectives: (1) determining if executive functions and food craving are linked, and (2) examining the predictors of highly palatable food intake and bland food intake. First, it was hypothesized that executive functions would be negatively associated with food craving. Second, it was expected that food craving would predict positively highly palatable food intake but not bland food intake. Third, it was predicted that executive functions would predict negatively highly palatable food intake and positively bland food intake.

Methods and material

Procedure

In this quasi-experimental design study, executive functions tasks were administered as well as a cue-provoked food craving protocol followed by a food intake protocol (see Fig. 1 for the study timeline). Participants attended two sessions on two consecutive days at the laboratory: the first day from 11:00 am to 12:30 pm and the second day from 12:30 pm to 1:30 pm. Fixed hours were chosen to reduce potential confounders such as hormone levels and fasting time, known to influence food craving and food intake [37–40]. Participants were also informed that they had to refrain from eating and drinking anything else than water at least 3 h prior to each visit. All participants reported having complied with these guidelines.

Participants

48 participants (35 females) with BMI ranging from 17.9 to 46.4 (see Table 1 for details) were recruited from employees and students' mailing lists of Université Laval. None of the participants reported a psychiatric or a neurological

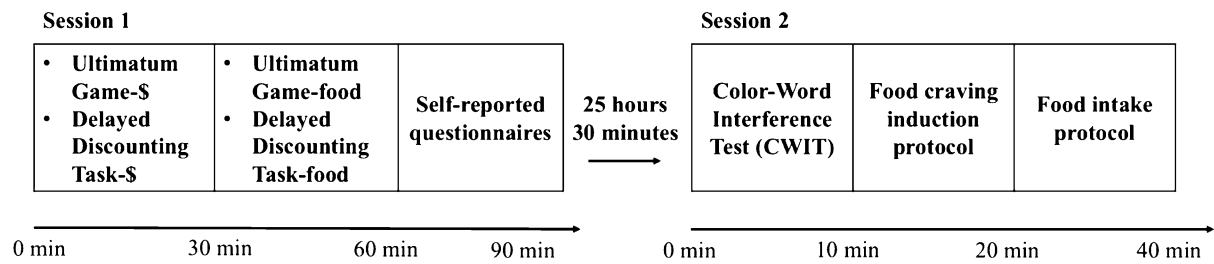


Fig. 1 Study timeline

Table 1 Socio-demographic data

	Range	<i>M</i> (ET)
Age (years)	20–40	26.94 (5.67)
BMI	17.9–46.4	27.85 (6.15)
%Fat	10.4–51.4	31.73 (10.94)
WC (cm)	24.2–47	35.39 (6.12)
Cardiovascular activity (min/week)	0–480	119.90 (115.66)

BMI body mass index, *%fat* percent body fat, *WC* waist circumference

condition and none reported taking psychotropic drugs. Further, participants with BMI over 25 had scores corresponding to the contemplation, action or maintenance stages of the Prochaska Stage of Change Scale [41] indicating they were motivated to lose weight. All participants liked at least two out of the three types of healthy food and two out of the three types of junk food presented in the food intake protocol as it was a requirement to participate in the study. The study received ethical approval from the institutional review board of the Institut de réadaptation en déficience physique de Québec (# 2015-412).

Executive functions

Cognitive inhibition and flexibility

The color–word interference test (CWIT) from the Delis–Kaplan Executive Function System (D-KEFS) [42] was used to measure cognitive inhibition and flexibility [43]. Condition 1 consisted of naming the ink color of squares, and condition 2 consisted of reading the color words printed in black ink. In condition 3, which measures inhibition, the participant named the color of the ink in which the words are written, this color being different from the semantic meaning of the word. In condition 4, measuring inhibition/flexibility, the participant must follow the instructions of condition 2 (reading) when the word is framed, and the instructions of condition 3 (inhibition) when the word is not framed.

Therefore, it requires switching from one instruction to another. For all conditions, participants were informed that they had to perform the task as fast as possible. Each participant performed all of the four conditions in the same order (condition 1 to condition 4). This task was chosen because it has consistently shown deficits in obese patients on the inhibition trial, namely condition 3 [see 14 for a review]. Moreover, the D–KEFS tasks are sensitive to small differences in executive functioning having been specifically designed to pick up mild impairments and to discriminate between people scoring near ceiling and floor and have good test–retest reliability [42, 44].

Decision making

Two versions of the delay discounting task [45] were used to measure decision making, one using virtual money (original task), and one using virtual food as a reward (chocolate chip cookies). In this task, participants must choose between an immediate reward and a delayed reward (monetary reward in the original version and chocolate chip cookies in the adapted food version), the delayed one being bigger. The amount of the immediate reward and the amount of the delayed reward varied from trial to trial so did the delays before obtaining the delayed reward. The monetary version of the task was always administered before the food version to avoid food craving during the task with money due to the repeated sight of chocolate chip cookies during the food version.

Decision making was also measured with the ultimatum game [46]. In this task, a fictive player must divide a certain amount of money (10\$) between him/her and the participant. For each trial, the participant must either accept or refuse the offer. If the participant accepts the offer, the money is divided as suggested, but if the offer is refused, neither the fictive player nor participant obtains any money. The original task with monetary rewards and a modified task with food rewards (chocolate chip cookies) were administered. The monetary version of the task was always completed before the food version to avoid craving during the completion of the monetary version.

Food craving

Participants filled out the Food Craving Questionnaire-State [FCQS; 47] before and after passive observation of food pictures. The FCQS included 15 items and participants were instructed to rate each of them on a visual analog scale (0–100). Passive observation of food pictures lasted 5 min and included 18 stimuli, such as hamburgers, watermelon, and cakes, which were presented twice for 8 s each in a pseudo-random order so that the same image could not be presented twice in a row. Ten were classified as calorie-dense food and eight as low-calorie food. Some pictures were drawn from the IAPS database (#7340-7330-7350-7400-7410-7450-7460-7475) while others were shot for the purpose of the study. Participants were instructed to pay attention to the pictures. After this first step, participants had to remain seated in front of the real food used in the food intake protocol for 5 min. They were then allowed to smell and touch the food, but they could not eat it. This protocol was based on Fregni et al. [48].

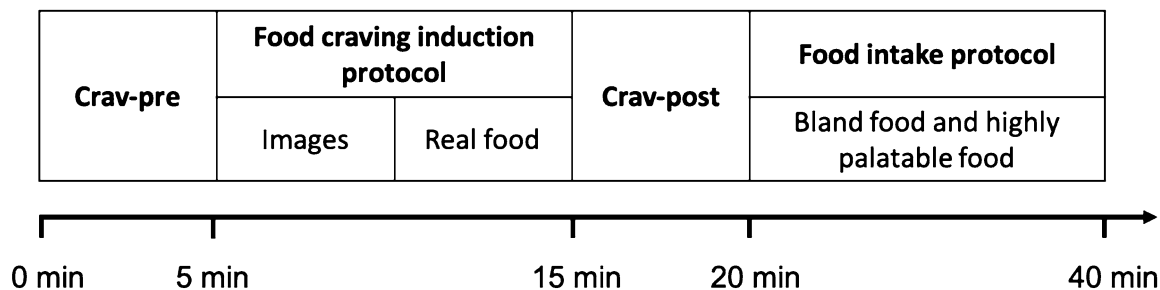
Food intake

The protocol was presented to participants as a food preference protocol to reduce social desirability bias. Participants were asked to fill out a questionnaire about the taste, smell, appearance and urge to eat each type of food. This protocol was identical to that of previous studies with respect to the deception procedure and questionnaires used [48–51]. The following amount of food was offered ad libitum to participants: 150 g of BBQ Ruffles[®] chips, 200 g of M&M's[®], 200 g of Skittles[®] candies, 150 g of whole grain crackers, 200 g of non-salted almonds and 200 g of dried raisins. The first three items were classified as highly palatable food and the latter three as bland food. The food of the two categories was approximately equivalent in calories, but the bland food was less processed

[52], contained more nutritive elements such as fibers, as well as less sugar, salt, and fat per portion. Each food of this protocol had been seen previously by participants in the food craving induction protocol. Participants were left alone in the room for 20 min and informed that they could eat as much as they wanted. The detailed timeline of the food craving induction and the food intake protocol is illustrated in Fig. 2.

Self-reported questionnaires

Food craving trait was assessed using the Food Craving Questionnaire Trait [FCQT; 47]. A modified version of the FCQT was used as each of the 39 items was rated on a visual analog scale (0–100) instead of a Likert scale. A higher score on that questionnaire indicates a greater general tendency to crave food. The Revised Restraint Scale [RS; 53], which consists of ten items, was used to measure cognitive restraint. Depressive symptoms were assessed with the Beck Depression Inventory [BDI; 54]. The questionnaire consists of 21 items rated on a four-point scale corresponding to depressive symptoms experienced in the last 2 weeks. A higher score indicates greater depressive symptoms. Anxiety symptoms were assessed using the Beck Anxiety Inventory [BAI; 55]. The questionnaire consists of 21 items referring to the last week. Each item is rated on a four-point scale. Attention deficit and hyperactivity disorder (ADHD) symptoms were measured using the Weiss Symptom Record [56]. This questionnaire includes two subscales, namely inattention and hyperactivity subscales, and is based on the diagnostic criteria from DSM-IV. Each item is rated on a four-point scale, zero corresponding to the absence of the symptom and three corresponding to the highest intensity of the symptom. Finally, hunger was measured on a visual analog scale (0–100) and participants were asked to report their weekly cardiovascular activity in minutes.



Baseline food craving (crav-pre); Food craving post-induction (crav-post).

Fig. 2 Detailed timeline of the food craving induction protocol and the food intake protocol. *crav-pre* Baseline food craving, *crav-post* Food craving post-induction

Anthropometric measurements

The height of each participant was objectively measured. Then, using this measure, the BMI and the percent body fat (% Fat) were calculated automatically by the InBody520 weighing machine. Waist circumference (WC) was taken by the experimenter at the point between the last rib and the upper part of the pelvic bone at the end of the expiration following the WHO guidelines [57].

All computerized tasks were programmed using E-prime software (Psychology Software Tools Inc., E-Prime 2.0, 2012) and presented on a 15-inch computer monitor with Windows 7, at a resolution of 1366 × 768 pixels.

Statistical analyses

The following variables were submitted to the analyses: time to complete the third and fourth conditions of the CWIT (in seconds; inhibition and inhibition/flexibility, respectively), impulsive rate towards monetary reward and towards food (# of impulsive responses/# total of responses; DDT), rejection rate of unfair offers (an offer of three or less) for monetary reward and for food (# rejected offers/# total of offers; UG), FCQS score before (pre) and after (post) the cue-induced food craving protocol, the total of grams eaten from highly palatable food (highly palatable food intake) and the total of grams eaten from bland food (bland food intake) in the food intake protocol, BMI, percent body fat (% fat), WC, the FCQT score, the BDI score, the BAI score, the Restraint Scale score and the Hunger score. First, two correlation matrices (Pearson correlations) were performed, the first one being one tailed (for variables for which there was a priori hypothesis) and the second one being two tailed (for variables without a priori hypothesis). Second, multiple

linear regressions were used to predict the total of grams eaten from highly palatable food, as well as from bland food with FCQS post, Restraint Scale score, BMI, inhibition, inhibition/flexibility, DDT with monetary reward, DDT with food, and FCQT as predictors. All statistical analyses were performed using SPSS software (version 23.0, SPSS Inc, Chicago, Illinois). The threshold for significance was set at $p < 0.05$ for all analyses.

Results

The dataset contained no missing data neither multivariate outliers (as assessed by an exploratory standard multiple regression with Cook and Mahalanobis' distance), therefore all analyses were performed on the whole sample (48 participants). For socio-demographic data, see Table 1.

Relationships between cognitive, psychiatric, eating and obesity variables

The first correlation matrix (one tail) yielded multiple significant correlations, see Table 2 for the complete results. The second correlation matrix (two tails) also yielded many significant correlations, see Table 3 for complete results. Results related to the hypotheses are reported below.

Correlations between cognitive factors and food craving

No significant correlations (one tailed) were found between FCQS pre and cognitive factors. However, FCQS post was significantly related to the inhibition/flexibility condition of the color–word interference test ($r = 0.29$;

Table 2 Correlation matrix (one tailed)

	Crav-post	Crav-pre	%Fat	BMI	WC	Inhibi ^a	//Flex ^a	HP-food	B-food
Crav-post	1								
Crav-pre	0.86**	1							
%Fat	0.03	0.21	1						
BMI	0.07	0.24	0.86**	1					
WC	0.07	0.27*	0.76**	0.91**	1				
Inhibi	0.19	0.09	0.22	0.22	0.17	1			
//Flex	0.29*	0.18	0.04	0.09	0.09	0.70**	1		
HP-food	0.45**	0.30*	−0.09	−0.12	−0.08	0.04	0.01	1	
B-food	0.16	0.17	−0.24	−0.03	−0.04	−0.18	−0.09	−0.04	1

crav-pre baseline food craving, *crav-post* food craving post-induction, *%fat* percent body fat, *BMI* body mass index, *WC* waist circumference, *Inhibi* Inhibition, *//Flex* Inhibition/Flexibility, *HP-food* highly palatable food intake; *B-food* Bland food intake

* $p \leq 0.05$

** $p \leq 0.01$

^aRefers to the time taken to complete the task. Higher scores reflect lower abilities

Table 3 Correlation matrix (two tailed)

	Reject-\$	Reject-food	Impul-\$	Impul-food	BDI	BAI	ADHD-I	ADHD-H	%fat	BMI	WC	Inhibi	I/Flex	HP-food	B-food	Crav-post	Crav-pre	FCQT	RS	Hung
Reject-\$	1																			
Reject-food	0.57**	1																		
Impul-\$	0.11	0.09	1																	
Impul-food	0.28	0.09	0.33*	1																
BDI	0.20	0.29*	0.16	0.33*	1															
BAI	0.12	0.08	0.03	0.10	0.35*	1														
Adhd-I	-0.05	0.34*	-0.15	-0.05	0.32*	0.43**	1													
Adhd-H	-0.20	-0.13	-0.28	-0.02	0.13	0.05	0.30*	1												
%fat	0.06	0.09	0.35*	0.30*	0.19	0.25	-0.06	-0.13	1											
BMI	-0.06	0.10	0.33*	0.25	0.16	0.16	0.05	-0.01	0.86**	1										
WC	-0.03	0.15	0.25	0.16	0.18	0.23	0.05	0.04	0.76**	0.91**	1									
Inhibi	-0.03	-0.06	0.42**	0.25	-0.00	0.16	0.10	0.01	0.22	0.22	0.17	1								
I/Flex	0.12	0.00	0.36*	0.03	0.03	0.06	0.04	0.11	0.04	0.09	0.09	0.70**	1							
HP-food	0.09	0.12	-0.04	-0.26	0.05	-0.01	0.05	-0.17	-0.10	-0.12	-0.08	0.05	0.01	1						
B-food	0.05	0.06	-0.10	-0.01	-0.00	-0.50	-0.02	0.08	0.24	-0.02	-0.05	-0.18	-0.08	-0.07	1					
Crav-post	0.35*	0.26	0.13	-0.01	0.41**	0.23	0.30*	-0.12	0.03	0.07	0.07	0.19	0.29*	0.46**	0.15	1				
Crav-pre	0.24	0.21	0.08	-0.04	0.41**	0.36*	0.25	-0.13	0.21	0.24	0.27	0.09	0.18	0.30*	0.17	0.86**	1			
FCQT	0.12	0.24	0.13	0.46**	0.65**	0.52**	0.32*	0.02	0.46**	0.41**	0.43**	0.12	-0.05	0.01	-0.08	0.43**	0.57**	1		
RS	0.01	0.12	0.19	0.20	0.34*	0.26	0.21	-0.09	0.70**	0.71**	0.72**	0.17	0.12	0.04	-0.25	0.26	0.38**	0.53**	1	
Hung	0.06	-0.15	0.16	0.00	-0.00	0.10	-0.09	-0.06	0.05	-0.10	0.06	0.21	0.44**	0.04	0.33*	0.40**	0.39**	-0.02	0.01	1

WC waist circumference, %fat percent body fat, RS restraint scale, FCQT food craving questionnaire trait, BDI beck depression inventory, BAI beck anxiety inventory, Impul-food impulsivity for food, Impul-\$ impulsivity for monetary reward, Crav-pre baseline food craving, Crav-post food craving post-induction, %Crav percent change in craving, B-food bland food intake, HP-food highly palatable food intake, Inhibi inhibition, I/Flex inhibition/flexibility, Reject-\$ rejection rate of monetary reward, Reject-food rejection rate of food, ADHD-I ADHD inattention, ADHD-H ADHD hyperactivity, Hung Hunger

* $p \leq 0.05$ *** $p \leq 0.01$

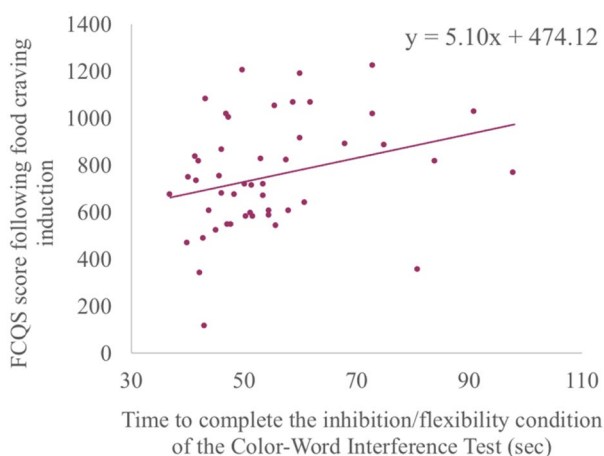
$p < 0.05$; one tailed) and the UG with monetary reward ($r = 0.35$; $p < 0.05$; two tailed). The correlation between FCQS post and inhibition/flexibility is depicted in Fig. 3.

Correlations between food craving and food intake

Both FCQS pre and FCQS post were associated to highly palatable food intake ($r = 0.30$; $p < 0.05$; $r = 0.45$; $p < 0.01$; one tailed). Interestingly, no significant correlations were found between food craving and bland food intake ($p > 0.10$).

Prediction of food intake

Two multiple hierarchical linear regression analyses were performed to test the prediction of highly palatable food ($M = 55.85$; $SD = 47.66$) and bland food intake ($M = 46.99$; $SD = 34.96$) using FCQS post, the Restraint Scale, BMI, inhibition, inhibition/flexibility, DDT with money, DDT with food and FCQT as predictors. The final model for junk food intake accounted for 27% of its variance ($p < 0.05$) with a unique contribution of FCQS post ($\beta = 0.45$; $p < 0.01$) and DDT with food ($\beta = -0.26$; $p < 0.05$). All other variables were excluded from the analyses, because they did not explain significant additional variance. The effect size (Cohen's $f^2 = 0.37$) for this regression is large [58]. According to bland food intake, the model was not significant ($p > 0.05$).



$r = 0.29$; $p < 0.05$; one-tailed
Food Craving Questionnaire State (FCQS)

Fig. 3 Correlation between FCQS post and inhibition/flexibility. $r = .29$; $p < 0.05$; one tailed. FCQS food craving questionnaire state

Discussion

This study examined the relationship between executive functions and food craving, as well as the predictors of food intake in a sample of adults with a wide range of BMIs (from underweight to class three obesity).

Links between executive functions and food craving

The negative relationship between inhibition/flexibility and cue-induced food craving partly confirmed the hypothesis regarding the relationship between executive functions and food craving. However, contrary to expectations, cognitive inhibition, impulsivity towards monetary rewards and towards food were not significantly related to food craving. Executive functions and state food craving were related to each other for the first time in this study. This association suggests that better inhibition and flexibility abilities are related to better control of food craving in the context of food craving induction, as there is a significant relationship between inhibition and flexibility abilities and cue-induced food craving, but not with tonic food craving. On the methodological level, this result suggests the importance of measuring cue-induced food craving rather than solely tonic food craving. Moreover, a recent study has found that eating disordered patients do not differ from controls regarding tonic food craving, but rather regarding food craving following induction [59], which underline the clinical relevance of this particular type of food craving.

Interestingly, this finding parallels the neuroimaging literature showing an underactivation of the cognitive control network (underlying executive functions) concomitant with an overactivation of the reward system (underlying food craving) in obesity [6–8]. Indeed, the results show that lower inhibition and flexibility capacities are related to higher food craving following induction, which is the behavioral parallel to the cerebral imbalance between the cognitive control network and the reward system.

Meanwhile, a recent study has shown that inhibition and flexibility is lower in obese patients high in food addiction traits (as measured by the Yale Food Addiction Scale) as compared to obese patients low in food addiction traits [27]. Moreover, food addiction has been related to higher food cravings [60, 61]. Therefore, one could hypothesize that the negative relationship between executive functions and food craving is explained by a third factor, namely food addiction. In future studies, this could be tested using a mediation model. This line of research would be interesting to better understand the mechanism behind the relationship between executive functions and food craving. Besides, this link between executive functions and food

craving reinforced the transdiagnostic value of executive functions in obesity and eating disorders, an idea that has been proposed recently [16, 17].

Finally, if future studies confirm this result, cognitive remediation of inhibition and flexibility could be added as a therapeutic component in treatments in the context of obesity as it has been suggested previously [17, 18]. Indeed, an improvement in cognitive inhibition and flexibility would entail a better control over food craving, particularly in an obesogenic environment, and therefore enhance cognitive control over food intake. Cognitive remediation to modulate eating behaviors has been tested with promising results [62–64]. Moreover, some evidence suggests that improvements in cognitive flexibility specifically predict greater weight loss and reduce sedentary behaviors as well as unhealthy eating habits [63, 64]. Of interest, these improvements in cognitive flexibility are produced by a manualized cognitive remediation therapy for obesity that is currently available [65].

Prediction of food intake

The hypothesis that highly palatable food intake but not bland food intake would be predicted by food craving was confirmed. It is noteworthy that these results were found in conditions where participants had not eaten for 3 h and, even though hunger did not predict food intake, whether the results would remain the same at satiety remains to be investigated. To our knowledge, this was the first study to directly compare the contribution of food craving in highly palatable food intake and bland food intake in an experimental food intake protocol. This result sheds light on the role of food craving in food intake and adds to the existing literature on its role in obesity. Indeed, as the presence of food craving seems to be associated with highly palatable food intake but not bland food intake, it could lead to deleterious health habits in the long term and therefore promote obesity and/or act as a barrier to weight loss. This is even more relevant as food craving has been related to waist circumference in the present study and to BMI and weight gain over time in previous studies [9, 10]. This result is not surprising and is in line with the literature showing that food cravings occur mostly towards sweets and fatty fast food [9] and that craving for a precise food would lead to the consumption of this same food [9, 34, 36]. However, while seeking weight loss, people could have made the conscious choice to avoid giving into their cravings and chosen the available alternative, in this case, the bland food provided. However, this was not the case. Therefore, the contribution of food craving to highly palatable food intake seems to be a phenomenon of clinical interest in the context of obesity and weight loss interventions. This is also in line with previous studies that have shown that food craving is associated with important clinical

outcomes. Indeed, food craving can differentiate between successful and unsuccessful dieters, with higher trait food craving in unsuccessful dieters [66]. Moreover, food craving is predictive of future weight gain [see 67 for a review] and a decrease in trait food craving is associated with weight loss [68]. Nevertheless, in contradiction with the results of the present work, a recent study suggests that food craving does not necessarily lead to food intake in people who are currently dieting [69]. The discrepant results might come from sample differences; the participants from the Smithson and Hill's study were all members of a group-based weight management program and were also older than the sample of this study. First, being part of a weight management program might have induced a social desirability effect [70–74] that would have prevented food intake despite the presence of food craving. Second, being older might come along with more experience in managing food craving which resulted in lower food intake. Nonetheless, more research is needed to clarify the variables implicated in this heterogeneity of results regarding the clinical impact of food craving in weight loss management.

Regarding the link between executive functions and food intake, the results are not in line with the initial hypothesis as executive functions did not predict significantly food intake. Interestingly, a recent study by Perpina et al. [16] has not found any relationship between cognitive flexibility as measured by the Wisconsin Card Sorting Test and eating pathology in a large sample of control, obese and eating disordered patients despite executive deficits in patients compared to control. However, another study from Graham et al. [26] found a positive correlation between perseverative errors in the Wisconsin Card Sorting Test, indicative of a lack of cognitive flexibility, and food intake over 3 days in an obese sample. Nonetheless, the correlation between food intake and the inhibition condition of the CWIT was not significant, just like in the current study. Hence, it is possible that the CWIT is not sensitive enough to capture the relationship between food intake and executive functions. Moreover, in the present study, the CWIT was not significantly related to BMI, but the delayed discounting task was. Besides, the present study and the study by Perpina et al. [16] included participants from a large range of BMI instead of recruiting solely obese people as Graham et al. [26]. The relationship between food intake and executive functions is possibly stronger in the obese population due to their executive deficits [see, 14, 15 for reviews], making this relationship harder to detect in a sample including a larger BMI range. Furthermore, the food intake protocol used by Graham et al. [26] might be more sensitive than the one used in this study as it extended over a few days instead of 20 min, and therefore could be more naturalistic as real meals were consumed. Social desirability could also have been lowered over the 3 days due to habituation, which is

unlikely to occur in a 20 min protocol. In brief, the protocol used in the present study might not be sensitive enough to detect the link between executive functions and food intake. Indeed, Allan et al. [25, 75] have shown that lower executive functions, as measured by the D-KEFS battery including the CWIT, were related to lower fruits and vegetables intake as well as higher high-calorie snacks intake in ecological settings in a general population sample. Therefore, it can be hypothesized that the same results would be found in an obese sample in those conditions where the social desirability bias is reduced to a minimum and a greater complexity of food choices is available, which would recruit executive functions to a larger extent.

Obesity indices were not found to be significant predictors of bland food intake and highly palatable food intake. Regarding the link between BMI and food intake, results from the literature are mixed. Some studies did not find any difference in food intake between obese and healthy weight groups [12, 13], similar to the results obtained in the present study. Another study found higher food intake in obese vs healthy weight participants in a laboratory setting [76]. Finally, a positive relationship between BMI and food intake was found when the latter was measured via a self-reported food frequency questionnaire [77]. Self-reported measures may reduce the social desirability bias related to food intake [70–74] compared to laboratory food intake where the experimenter is present or is known to assess food intake afterward. The idea that social desirability might explain negative results regarding food intake and BMI following cue-induced craving has been proposed previously [13]. Moreover, in the present study, overweight and obese participants were motivated to lose weight at the time of the study (as measured by the Prochaska Stage of Change Scale), possibly leading to a different behavioral pattern than the general overweight and obese population, which typically also includes a number of people that do not specifically aim at losing weight. Unfortunately, as this factor is generally not considered in other studies, it is not possible to do any comparison in this regard. Moreover, the fact that the experimenter knew the participant wanted to lose weight (as disclosed via the Prochaska Stage of Change Scale) may also have enhanced the social desirability bias related to food intake in participants [70–74]. Interestingly, a recent meta-analysis concluded that there was no difference between lean and overweight groups on the effect size of the impact of food craving on eating behaviors [67].

Finally, cognitive restraint is not a predictor of food intake, a result that is in line with a recent study [78]. However, in the same study, the type of food cues influences food intake in restrained eaters, but not in unrestrained eaters [78]. Indeed, grapes cues lead to lower food intake than both cookie cues alone and cookies and grapes cues in restrained eaters. Altogether, the study of Kemps et al. [78]

suggests that the interaction between cognitive restraint and the type of food cues need to be considered to better predict food intake, which was not the case in the present study. This might explain the absence of contribution of cognitive restraint to food intake. Of note, the present study corresponds to the cookies and grapes condition in the study of Kemps et al. [78], as every participant was exposed to highly palatable food as well as bland food in the food craving induction protocol. This methodological aspect needs to be kept in mind to reproduce the results of the present study.

Limitations

Even though the present study adds to the existing literature regarding food craving, executive functions, and food intake, its limitations need to be underlined. First, the relatively small sample size is worth mentioning and additional studies with larger samples are needed, particularly considering the large range of BMI included in the present study. Second, as this is the first study to show a relationship between executive functions and food craving, this result needs to be replicated in future studies. Third, even though the food intake protocol has high internal validity, it lacks external validity and social desirability is a highly probable confound. Indeed, the food intake protocol was administered in laboratory settings and the food consumed was not a complete meal even though it was consumed at lunchtime while participants had not eaten for 3 h. This raises concerns regarding how it transposes into day-to-day life. Therefore, future studies need to address this issue, possibly by measuring social desirability and/or by using real meals instead of snacks.

Conclusion

To conclude, this study supports the link between food craving and food intake and showed for the first time a specific contribution of food craving to highly palatable food intake but not to bland food intake in a laboratory setting, highlighting the potential influence of food craving in obesity and weight loss interventions. Finally, the association between lower cognitive inhibition and flexibility abilities and susceptibility to food craving induction is of great importance in our obesogenic environment, opening future research questions regarding the possible benefits of a cognitive remediation program for obesity treatment.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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