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Executive function in individuals with clinically significant weight loss via behavioral intervention

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Abstract

Background: Executive function (EF) is associated with obesity development and self-management. Individuals who demonstrate or self-report poorer EF performance tend to have poorer short-term outcomes in obesity treatment. There may be distinct behavioral self-management strategies and EF domains related to initial weight loss as compared to weight loss maintenance.

Objective: To characterize EF in individuals who achieved clinically significant weight loss via behavioral intervention and examine potential differences in EF between those who maintained versus regained lost weight.

Methods: Participants who previously achieved ≥5% weight loss via lifestyle intervention were included ($N = 44$). "Maintainers" ($n = 16$) maintained this minimum level of weight loss for ≥1 year. "Regainers" ($n = 28$) regained some or all initially lost weight. Performance-based EF, intelligence quotient, health literacy, depression, anxiety, binge eating, demographics, and medical/weight history were assessed using a cross-sectional design. Descriptive statistics and age-, gender-, education-adjusted reference ranges were used to characterize EF. Analyses of covariance were conducted to examine EF differences between maintainers and regainers.

Results: The sample consisted primarily of females with obesity over age 50. Approximately half self-identified as African–American. Decision-making performance was better in maintainers than regainers ($p = 0.003$, ${}_{part}\eta^2 = 0.19$). There were no differences between maintainers and regainers in inhibitory control, verbal fluency, planning/organization, cognitive flexibility, or working memory ($ps > 0.05$, ${}_{part}\eta^2$s $= 0.003–0.07$). At least 75% of the sample demonstrated average-above average EF test performance, indicated by scaled scores ≥13 or t-scores > 60.

Conclusions: Most individuals with obesity who achieved clinically significant weight loss via behavioral intervention had average to above average EF. Individuals who maintained (vs. regained) their lost weight performed better on tests of decision-making.

KEYWORDS
adults, behavioral intervention, executive function, maintenance, obesity, regain, weight loss

1 | INTRODUCTION

Over two-thirds of US adults have overweight/obesity,[1] indicating a greater need for obesity treatment and understanding of factors associated with weight management. One of the primary approaches for treating obesity is behavioral weight loss, also known as lifestyle intervention, which can result in clinically meaningful reductions in weight and improvements in other markers of health.[2,3] Though evidence strongly supports that modest weight loss can be accomplished via behavioral approaches, over half of the lost weight is regained within 2 years. In contrast, approximately 20% of individuals who lose weight successfully maintain this lost weight for an extended period of time.[4] Explanations for weight regain or weight loss maintenance are not well known, and continued investigation of factors for successful weight loss maintenance is needed.[5]

One factor related to successful weight loss and weight loss maintenance is an individual's self-management skills, including goal-setting, self-monitoring, problem-solving, and action-planning.[6,7] These self-management skills represent higher order cognitive processes referred to as executive function (EF). EF has been associated with self-management skills,[8] obesity risk,[9] and weight status (i.e., obesity or nonobesity).[10] Studies to date suggest that the association between EF and body mass index (BMI) may be bidirectional, such that poorer EF may predict higher BMI levels, and higher BMI levels may compound EF deficits.[11] For example, children who perform more poorly on tests of EF tend to have poorer weight outcomes following behavioral treatment,[12] while individuals with better performance on tests of EF have demonstrated greater weight loss following bariatric surgery.[13] The possible mechanisms of the relationships that have been identified between EF and weight management have gotten more attention in the last several years, with a focus on behavioral mechanisms such as eating behavior[14] and physical activity.[15] While there is limited evidence for the predictive relationship between EF and weight loss outcomes in child samples and bariatric surgery, research is lacking on the role of EF in self-management of weight loss maintenance following behavioral obesity treatment in adults.

A better understanding of the relationships between EF and weight loss maintenance is particularly warranted given the distinction between behavioral self-management strategies required for initial weight loss (e.g., plan ahead for meals; self-monitor exercise) and weight loss maintenance (e.g., reward oneself for adhering to diet or exercise plan).[16] In fact, a recent empirical and conceptual review of EF and weight management concluded that research on weight loss and EF is only beginning to emerge, and research specifically focused on the role of EF in weight loss maintenance is virtually absent.[17] This review describes an evidence-based model for the relationship between EF domains, health behaviors (e.g., physical activity and eating behavior), and their relationship with initial weight loss and weight loss maintenance. Importantly, recent evidence highlights the bidirectional nature of the relationships between EF and weight-related health behaviors, such that low physical activity levels can lead to poorer EF, and poorer EF can predict lower physical activity levels.[18] Moreover, existing studies examining EF and weight loss often fail to include comprehensive assessments of EF despite its multidimensional nature. Along these same lines, psychopathology and disordered eating can also predict weight loss outcomes and share the common mechanisms of impulsivity and dysregulation.[19] Thus, a broad characterization of EF performance and other factors potentially related to weight loss (e.g., psychological functioning and premorbid intelligence quotient [IQ]) following weight loss is warranted, including an examination of potential differences in EF between individuals that have maintained or regained lost weight.

The primary purpose of this project was to examine the association between EF and long-term weight management. Individuals who had successfully completed a behavioral weight loss intervention, achieved clinically significant initial weight loss, and subsequently either maintained or regained their weight loss were contacted to assess performance-based EF (inhibitory control, verbal fluency, planning/organization, cognitive flexibility, working memory, and decision-making). The specific aims of the study were to (1) characterize EF in individuals who achieved clinically significant weight loss via behavioral intervention and (2) examine whether there were differences in EF between those who maintained versus regained lost weight. It was hypothesized that individuals who maintained lost weight would exhibit better scores on EF measures compared to individuals who did not maintain lost weight.

2 | METHODS

2.1 | Participants

A total of $N = 44$ participants were enrolled in the study. Participants were recruited into the ancillary cross-sectional study following completion of the parent behavioral weight loss intervention study, Improving Weight Loss Maintenance Through Alternative Schedules of Treatment (ImWeL, NCT02487121) which was conducted at the University of Alabama at Birmingham.[20] The intervention included evidence-based content focused on dietary modification, increased physical activity, and behavioral strategies designed to promote adherence to these lifestyle changes (e.g., self-monitoring, problem-solving, and goal-setting). Weekly contacts were delivered by trained interventionists with the goal of achieving 5%–10% weight reduction during the first 4 months of treatment. Following the initial 4-month intervention, ImWeL included a 12-month extended care program that included up to 12 additional visits that were designed to promote adherence to long-term behavioral strategies supportive of weight loss maintenance.

Individuals were eligible to be recruited for the study if ≥ 5% weight loss was achieved during the aforementioned intervention. Eligibility was confirmed based on study records of weight loss history. Participants were enrolled on a rolling basis across a 6-month period, which occurred 2–4 years after their completion of the ImWeL extended care program. Participants for the study were classified as either weight loss maintainers or weight loss regainers. Criteria for weight loss maintainers were derived from criteria used in other weight loss maintenance studies.[21,22] Weight loss maintainers lost ≥5% of their initial body weight during treatment and maintained this minimum level of weight loss for ≥1 year. Regainers lost ≥5% of initial body weight during treatment but experienced regain of some or all of their initially lost weight such that their body weight returned to within 5% of their pre-treatment values.

Participants with a history of bariatric surgery, unintentional weight loss since participating in the previous weight loss trial, or a medical condition that may have influenced body weight were excluded from the study. The study was approved by the local Institutional Review Board.

2.2 | Procedure

Individuals were recruited via mailed letters detailing the study's purpose and activities. Letters were followed by telephone calls from staff to assess prospective participants' interest and eligibility. Interested individuals were scheduled to complete in-person visits to provide informed consent, confirm eligibility, and complete a battery of performance-based EF measures (described below). This study utilized a cross-sectional assessment of EF. All measures were administered by two masters-level trained technicians using standardized procedures. Given previously demonstrated associations between EF and sociodemographic characteristics, BMI, depression, anxiety, binge eating, IQ, and academic achievement,[23–25] these constructs were also assessed and are described in more detail below. Testing lasted approximately 2–2.5 h and was conducted in a private room with only the participant and technician present. All test sessions were video recorded with the participant's consent and reviewed for quality assurance purposes. Technicians completed several weeks of training and were required to achieve 95% inter-rater reliability with the supervising PhD-level psychologist conducting training prior to commencing participant assessments. Weekly supervision was held with technicians and two supervising PhD-level psychologists to resolve administration or scoring concerns.

2.3 | Measures

2.3.1 | Demographic information

Participants were asked to provide their age, educational attainment, medical history, race/ethnicity, marital status, and household income.

2.3.2 | Anthropometric measurements

Height and weight were measured, respectively, to the nearest 0.1 cm and 0.1 kg with shoes removed using a wall-mounted stadiometer and digital scale. Measured height and weight were used to calculate BMI (kg/m^2).

2.4 | Executive function assessment battery

2.4.1 | Wechsler Adult Intelligence Scale Digit Span subtest, fourth edition

The Wechsler Adult Intelligence Scale Digit Span subtest, fourth edition (WAIS-IV Digit Span) is a commonly used measure of working memory.[26] In this task, the individual is read a string of digits in increasing length and requires the examinee to repeat the number string verbatim or with some form of mental manipulation. A scaled score is produced based on overall performance.

2.4.2 | Delis-Kaplan Executive Function System Color-Word Interference Test

The Delis-Kaplan Executive Function System (DKEFS) Color-Word Interference Test, Condition 3, measures response inhibition.[27] The task includes color names printed in contrasting ink colors, and the examinee must identify the color of the ink the letters are printed in and avoid reading the printed word. A scaled score is produced based on time to completion.

2.4.3 | DKEFS Verbal Fluency Test

The DKEFS Verbal Fluency Test (VFT), Letter Fluency condition, assesses verbal functioning and phonemic fluency.[27] The Letter Fluency condition requires the participant to say as many words as possible that begin with a certain letter over the course of 60 s. A scaled score is generated from the total number of correct responses.

2.4.4 | DKEFS Trail Making Test

DKEFS Trail Making Test (TMT), Condition 4, assesses cognitive flexibility (i.e., set-shifting abilities).[27] The participant is required to alphabetically and numerically sequence numbers and letters, alternating between the numbers and letters. A scaled score is produced based on time to completion.

2.4.5 | DKEFS Tower Test.

The DKEFS Tower Test measures planning and problem-solving ability.[27] The participant is given five different-sized disks pre-arranged on a three-peg base and told to build a series of nine towers that become progressively more difficult. Pictures are provided of each tower along with a set of specific rules to follow. The Total Achievement Score is a scaled score based on the total number of towers built correctly in the allotted time and the total number of moves required to build them.

2.4.6 | Iowa Gambling Task

The Iowa Gambling Task (IGT) was originally developed to assess decision-making deficits in individuals with neurological damage.[28] Administration is computer-based and participants are instructed to choose a card from one of four decks over the course of 100 trials with the ultimate goal of winning money. After each card is selected, the computer indicates whether money was won or lost. Thus, each deck has different characteristics that determine its advantageousness and riskiness. A US Census-matched T-score is produced based on the Total Net Score.

2.5 | Other relevant measures/covariate measures

2.5.1 | Patient Health Questionnaire depressive symptoms scale

The Patient Health Questionnaire (PHQ-8)[29] is a brief self-administered measure designed to assess depressive symptoms in the past two weeks. Response options range from "Not at All" to "Nearly Every Day" (0–3). Higher scores indicate greater severity of depressive symptoms.

2.5.2 | Generalized Anxiety Disorder scale

The Generalized Anxiety Disorder (GAD-7)[30] is a brief clinical measure to assess symptoms of generalized anxiety over the past 2 weeks. Response options range from "Not at All" to "Nearly Every Day" (0–3). Higher scores are associated with greater functional impairment in real-world settings.

2.5.3 | Binge Eating Scale

The BES is a 16-item measure of the presence and severity of binge eating behaviors.[31] The individual is asked to choose which of four statements characterizing behaviors, emotions, and/or cognitions best describes them. Higher scores indicate greater binge eating severity.

2.5.4 | Wechsler Test of Adult Reading

The Wechsler Test of Adult Reading (WTAR) is a list of 50 words requiring the examinee to pronounce each word aloud.[32] As word reading recognition is relatively stable in the face of cognitive decline or brain injury, the WTAR is used to estimate premorbid intellectual functioning.

2.5.5 | Rapid Estimate of Adult Literacy in Medicine–Short Form

The Rapid Estimate of Adult Literacy in Medicine–Short Form (REALM-SF)[33] is a brief health literacy assessment tool that requires the examinee to pronounce seven medical terms with a possible total score of 7. Higher scores correspond with higher estimated reading levels ranging from 0 (3rd grade or less) to 7 (9th grade or above). The REALM-SF has been validated against the revised Wide Range Achievement Test, and scores are highly correlated.[34]

2.6 | Data analyses

Descriptive statistics and comparison to published norm-based reference ranges were used to characterize EF in individuals who achieved clinically significant weight loss via behavioral intervention (Aim 1). Borderline to impaired scores were defined as scaled scores ≤ 5 or t-scores <40. Above average to superior scores were defined as scaled scores ≥ 13 or t-scores >60.[35,36] Analyses of covariance (ANCOVAs) were conducted to examine whether there were differences in EF between those who maintained versus regained lost weight (Aim 2). Covariate testing was conducted for Aim 2. Premorbid IQ was the only variable consistently associated with EF domains, and thus was included as a covariate in all analyses. Other potential covariates demonstrated weak associations with EF ($r < 0.2$). The majority of EF test scores are interpreted using published, norm-based samples (adjusting for age, gender, and/or education); thus, where appropriate, applicable demographic variables were not included as covariates given the adjustment during scoring. As the primary goals of the study were to evaluate EF among weight loss maintainers and regainers, all results are stratified by these two groups. The total number of participants who completed the study and were included in data analyses was $N = 44$ (maintainers = 16; regainers = 28). There was no missing data.

3 | RESULTS

3.1 | Sample characteristics

Sample characteristics are displayed in Table 1. The sample consisted primarily of women over the age of 50, and the majority of individuals currently met criteria for obesity (>30 kg/m^2). Approximately half of the sample (55%) self-identified as African–American. The mean initial percent weight loss during the previous behavioral intervention was similar between maintainers and regainers (−16.7% vs. −15.4%, respectively) and was much greater than the 5% reduction in weight required for enrollment in this study. The average participant in this sample started at an initial weight of 88 kg and had an initial 16% weight loss (14 kg), resulting in a weight of 74 kg prior to the weight loss maintenance phase. As a maintainer, on average, the participant would have maintained 76% of the 14 kg lost (11 kg), resulting in a final weight of 77 kg. Alternatively, as a regainer, on average, the participant would have regained all of the lost weight (14 kg) and an additional 23% of the previously lost weight (3 kg), resulting in a final weight of 91 kg.

3.2 | EF in individuals who maintained versus regained lost weight

Table 2 displays the mean performance scores, ANCOVA results, and comparison effect sizes of EF performance in weight loss maintainers and regainers. Normed EF domain scaled scores are $M = 10$, $SD = 3$ with the exception of decision-making, which are T-scores ($M = 50$, $SD = 10$). The mean scaled scores on inhibitory control, verbal fluency, planning/organization, cognitive flexibility, and working memory for both maintainers and regainers are in the range of average performance (9.61–11.56), suggesting intact functioning across these EF domains on average in both groups. There were no significant differences between maintainers and regainers on performance of EF tests in the domains of inhibitory control, verbal fluency, planning/organization, cognitive flexibility, or working memory (ps > 0.05, ${}_{\text{part}}\eta^2$s = 0.003–0.07). Similarly, decision-making performance for maintainers and regainers, respectively, was within the average range ($M = 53.56$ and $M = 46.39$), also suggesting intact decision-making on average in both groups. However, maintainers demonstrated significantly better decision-making performance than regainers [M(SD) = 53.56 (6.54) versus 46.39 (7.56) t-score, $p = 0.003$, ${}_{\text{part}}\eta^2 = 0.19$].

3.3 | Impaired and above average EF performance in individuals who maintained versus regained lost weight

Table 3 displays the frequency of impaired performance and above average performance on EF domain tests in weight loss maintainers and regainers as well as the sample as a whole. For the overall sample, borderline to impaired performance on EF tests ranged from 0% (working memory) to 15.9% (decision-making). Alternatively, the overall sample's above average to superior performance on EF tests ranged from 6.8% (decision-making) to 25.0% (cognitive flexibility). There was one statistically significant difference between maintainers and regainers in terms of the frequency of impaired EF, which was in the decision-making domain. While there were no maintainers who scored in the borderline/impaired range on decision-making, 25% ($n = 7$) of regainers had borderline to impaired performance in this domain. There were no differences between maintainers and regainers on any EF domains in the proportion of those demonstrating above average performance scores.

4 | DISCUSSION

This is the first known study to conduct a comprehensive investigation of executive function (EF) and its association with weight loss maintenance and regain following clinically significant weight loss via behavioral intervention. In support of the first hypothesis, most individuals who were successful in losing a clinically significant amount of weight through a previous behavioral intervention had *intact* EF. In fact, at least 75% of the sample demonstrated average or above average performance across EF measures. In partial support of the second hypothesis, individuals who maintained (vs. regained) their lost weight performed better in the *decision-making* domain of EF. This was considered a medium to large effect; however, it is not known how the difference in IGT performance may translate to behavioral or functional differences, as both maintainers and regainers performed on average above the clinically impaired cutoff t-score of 39. There were no other differences in EF performance (e.g., inhibitory control, planning/organization, cognitive flexibility and working memory) identified between maintainers and regainers.

Thus, the results of this study suggest that there may be domain-specific associations between EF and weight loss maintenance. Specifically, decision-making performance was better on average in maintainers than regainers. Notably, no maintainers performed in the borderline to impaired range of decision-making, as compared to the 25% of the regainer group who demonstrated borderline to impaired decision-making. A recent review was published on decision-making processes that relate to weight management, with an emphasis on food decision-making (e.g., fruit/vegetable intake).[37] Food decision-making may become more independent as an individual completes a behavioral program, as there is less reliance on provided resources such as dietician/interventionist support and structured meal plans. Furthermore, findings from the National Weight Control Registry suggest that consistency in dietary adherence predicts long-term weight loss maintenance,[7] although dietary intake and physical activity were not measured in the current study. Taken together, this could explain the study findings that decision-making was significantly related to weight loss maintenance (vs. regain), given that individuals who successfully enter and sustain weight loss maintenance

TABLE 1 Sample characteristics stratified by weight loss maintainers and regainers ($N = 44$)

Sample Characteristic	Maintainer ($n = 16$)	Regainer ($n = 28$)	Total ($N = 44$)	*p*-value**
		M (SD)		
Age (range 32–78)	53.8 (10.9)	59.5 (11.9)	57.4 (11.7)	0.12
BMI (range 27–45)	31.2 (3.5)	34.4 (3.8)	33.2 (4.0)	**0.01**
Initial% weight loss	16.7 (7.5)	15.4 (7.3)	15.9 (7.3)	0.58
% Weight loss maintained[a]	76.1 (29.2)	−23.4 (57.0)	12.8 (68.4)	**<0.001**
		% (n)		
Female	87.5 (14)	96.4 (27)	93.2 (41)	0.35
Race (100% non-Hispanic ethnicity)				0.87
African–American	56.3 (9)	53.6 (15)	54.5 (24)	-
Caucasian	43.8 (7)	46.4 (13)	45.5 (20)	-
Married	56.3 (9)	42.9 (12)	47.7 (21)	0.40
Full/Part-time employed	75.0 (12)	75.0 (21)	75.0 (33)	0.88
Annual family income				0.23
<$30,000	6.3 (1)	14.3 (4)	11.4 (5)	-
$30–50,000	31.3 (5)	32.1 (9)	31.8 (14)	-
$50–80,000	12.5 (2)	32.1 (9)	25.0 (11)	-
>$80,000	50.0 (8)	21.4 (6)	31.8 (14)	-
Highest degree education				0.33
≤HS degree	0.0 (0)	10.7 (3)	6.8 (3)	-
Some college or associate's	25.0 (4)	14.3 (4)	18.2 (8)	-
4-year college or higher	75.0 (12)	75.0 (21)	75.0 (33)	-

[a]weight loss is expressed as % maintained, thus the negative mean value indicated for regainers demonstrates that the average regainer did not maintain any lost weight but rather regained an amount of weight that placed them beyond their initial weight; an alternative interpretation of these values is average % weight regained which are 23.9% and 123.4%, respectively, for maintainers and regainers.

**p-value corresponding to mean comparisons for maintainers and regainers.

TABLE 2 ANCOVA results comparing EF domains between weight loss maintainers ($n = 16$) and regainers ($n = 28$)

EF Domain	Maintainer M (SD)	Regainer M (SD)	F df (1,40)	*p*-value	Partial η2
Inhibitory control	10.75 (2.08)	9.79 (2.50)	1.67	0.21	0.04
Verbal fluency	11.56 (3.29)	9.71 (3.41)	3.02	0.09	0.07
Planning/Organization	10.25 (2.75)	9.71 (2.64)	0.27	0.61	0.006
Cognitive flexibility	10.94 (2.21)	10.14 (3.25)	0.65	0.42	0.02
Working memory	9.94 (1.84)	9.61 (2.30)	0.12	0.73	0.003
Decision-making	53.56 (6.54)	46.39 (7.56)	9.66	0.003	0.19

Notes: Means and standard deviations presented are unadjusted values; ANCOVAs adjust for premorbid IQ; EF domain scores are scaled scores; ($M = 10$, SD $= 3$) with the exception of decision-making which are T-scores ($M = 50$, SD $= 10$).

Abbreviations: EF, executive function; IQ, intelligence quotient.

*significance level set at $p < 0.05$.

may rely more on independent decision-making for food and physical activity choices.

Previous studies that have examined the association between weight loss and EF demonstrate mixed results,[17,38] which makes it difficult to determine whether the findings of this study are consistent with previous research. For instance, inhibitory control is a commonly studied domain of EF that has been associated with short-term weight loss as well as eating and appetitive behaviors.[14]

TABLE 3 Frequency of impaired and above average performance scores on executive function tests among weight loss maintainers ($n = 16$) and regainers ($n = 28$)

Executive Function Domain	Maintainer ($n = 16$) % (n)	Regainer ($n = 28$) % (n)	Total ($N = 44$) % (n)	Fisher's Exact p
Borderline to impaired scores[a,b]				
Inhibitory control[a]	0.0 (0)	7.1 (2)	4.5 (2)	0.5
Verbal fluency[a]	6.3 (1)	10.7 (3)	9.1 (4)	1.0
Planning/Organization[a]	6.3 (1)	7.1 (2)	6.8 (3)	1.0
Cognitive flexibility[a]	0.0 (0)	10.7 (3)	6.8 (3)	0.3
Working memory[a]	0.0 (0)	0.0 (0)	0.0 (0)	-
Decision-making[b]	0.0 (0)	25.0 (7)	15.9 (7)	0.04
Above average to superior scores[a,b]				
Inhibitory control[a]	18.8 (3)	14.3 (4)	15.9 (7)	0.7
Verbal fluency[a]	31.3 (5)	14.3 (4)	20.5 (9)	0.3
Planning/Organization[a]	25.0 (4)	10.7 (3)	15.0 (7)	0.2
Cognitive flexibility[a]	25.0 (4)	25.0 (7)	25.0 (11)	1.0
Working memory[a]	6.3 (1)	14.3 (4)	11.4 (5)	0.6
Decision-making[b]	12.5 (2)	3.6 (1)	6.8 (3)	0.5

Note: Fisher's Exact Test used when cell values are less than 5; Bonferroni correction applied.

[a]Borderline to impaired scores: Scaled Scores ≤ 5; Above Average to superior scores: Scaled Scores ≥ 13.

[b]Borderline to impaired scores: T-scores < 40; Above Average to superior scores: T-scores > 60.

Importantly, though, inhibitory control has also been associated with long-term response to bariatric surgery, such that poorer inhibitory control was demonstrated in individuals who were "poor (weight loss) responders" in comparison to "good responders" in an examination 12 years postsurgery.[39] Yet, results from this study did not demonstrate a relationship between inhibitory control and weight loss maintenance patterns following behavioral treatment of obesity.

A recent systematic review including longitudinal studies of EF and obesity[40] highlights the discrepant results of previous studies. For example, 6 of the 11 identified longitudinal studies examining cognitive flexibility and obesity did not observe a significant relationship, which is consistent with the results from this study. However, 2 of the 5 studies that did find a significant cognitive flexibility-obesity association found that poorer cognitive flexibility was associated with less weight loss over time. Other recent findings in adolescents suggest that the change in certain domains of EF (e.g., cognitive flexibility[41] and inhibitory control[42]) during behavioral treatment may be a more meaningful predictor of long-term weight loss outcomes than baseline EF. However, Raman and colleagues (2017)[43] conducted an RCT in adults with obesity comparing a traditional behavioral weight loss treatment plus cognitive remediation training condition to a traditional behavioral weight loss treatment only. There were minimal changes in EF for individuals who received behavioral weight loss treatment only, at post-treatment and 3-month follow-up. The effect sizes of the change in EF from baseline to 3-month follow-up for the behavioral weight loss condition only were very small (Cohen's $d = -0.05$ to -0.01), as compared to the large changes in EF observed in the behavioral weight loss condition plus cognitive remediation training (Cohen's $d = 0.78$–1.7). While EF changes have been observed in parents during family based behavioral treatment for obesity, evidence to date suggests that minimal change in EF occurs in adults over the course of standard behavioral treatment for obesity in adults.

These mixed findings of EF and long-term weight loss in the literature are partially attributable to methodological differences such as variability in EF measurement tools, focus on short-term as compared to long-term weight loss, and treatment modality (e.g., behavioral vs. surgical). There is substantial variability in EF measurement tools within the weight loss literature.[40] While valid and reliable EF measures were selected for this study, it may be possible that these measures were not sensitive enough (as compared to other study measures) to identify the nuances between these two generally high-performing groups of individuals. It is also possible that the lack of difference between maintainers and regainers in some domains of EF was due to the sample including only participants who were initially able to achieve greater than 5% weight loss, potentially suggesting intact EF. This seems to be supported by the data demonstrating the mean EF performance scores in every domain were in the average range based on U.S. age-, gender-, and/or education-based norms. The average initial weight loss in participants from the study, for both maintainers ($M = 16.7\%$) and regainers ($M = 15.4\%$), was also rather high for a behavioral intervention. Moreover, 93% of the sample reported at least some college education, which could be related to the unanticipated lack of variability in EF.

Additionally, while the study sample achieved a high level of initial weight loss for behavioral intervention, a threshold of weight loss that might be associated with appreciable variation in EF may not have been observed. For example, better cognitive function at 12-weeks post-bariatric surgery predicted greater postoperative percent weight loss and BMI at 36 months, even after adjusting for baseline cognitive function.[44] In addition, the present study sample still falls within the BMI range for obesity on average. Indeed, the most consistent relationship between EF and weight loss has been observed in cases of bariatric surgery,[13,39,45] which are capable of achieving weight loss outcomes that typically exceed those of behavioral interventions. Furthermore, the underlying physiological mechanism(s) between EF and obesity is unknown. Weight loss and the negative energy balance that is necessary for weight loss may impact additional physiological functions, such as sleep, cardiovascular function, physical activity, and brain function, all of which are also known to have an impact on EF.[46,47]

Furthermore, there is a disconnect between common theoretical models of EF and the measures most commonly used to assess EF in this population. For example, Gettens and Gorin[17] map the three major EF domains of shifting, updating, and inhibition onto specific weight loss maintenance behaviors such as self-weighing and meal planning. While the performance-based measures used in this protocol objectively assess these same EF domains (e.g., DKEFS Trails as a measure of shifting/cognitive flexibility; DKEFS Color-Word Interference as a measure of inhibition), it is not clear whether these "nonspecific" EF measures are sensitive to weight loss maintenance behaviors. To add to this complexity, multidimensional EF assessments integrating subjective, objective, and imaging data are becoming increasingly useful as each of these methodological approaches appears to contribute meaningful, independent data. However, inclusion of all of these assessments may be impractical; thus, only one of these approaches is often used when examining EF in weight management.

Study limitations should be taken into consideration including the lack of pre-treatment/weight loss measures of EF, which limits an understanding of the effect that previous treatment may have had on participants' EF. The exact length of time from completion of behavioral treatment to follow-up cognitive assessment is unknown and may also have influenced the findings. In addition, while age- and education-normed scoring of the EF tests were used, these norms sometimes include broad categories that may not capture the full range of score variability across certain categories (e.g., racial/ethnic groups and older adults). Furthermore, the lack of a comparison group in this study prohibits evaluation of the EF performance of maintainers and regainers in reference to individuals with obesity who did not receive treatment. Moreover, the study sample was small ($N = 44$) with underrepresentation of men, younger adults, and individuals with less than some college experience. The effect sizes ranged from very small to medium/large and may be unstable given smaller cell sizes, so the generalizability and clinical relevance of observed differences is uncertain. Finally, while it is likely that EF and weight loss share a bidirectional relationship, the study is limited by design to characterize EF in weight loss maintenance rather than to identify the causal pathways of the association. The study also had a number of strengths, including the wide age range represented and relatively balanced sample of African–Americans and non-Hispanic Caucasians. In addition, a diverse battery of validated, objective measures of EF constructs with careful attention to assessment fidelity was utilized in the study protocol. Finally, this study offers a novel approach and addition to the EF and weight management literature by examining differences in EF among maintainers and regainers of lost weight following behavioral weight loss treatment.

Future research should examine pretreatment measurement of EF to predict behavioral obesity treatment outcomes and may be particularly useful when focusing specifically on EF in individuals who initially attempted weight loss but did not achieve a clinically meaningful response. In addition, cue-based (vs. general) measures of EF could be a fruitful avenue of exploration to determine whether self-regulatory concerns manifest primarily in "weight-related" situations rather than globally as measured here. Other important factors, such as physical activity, dietary intake, and self-efficacy that could have influenced or help to explain the findings that decision-making was related to weight loss maintenance were not assessed and should be considered in future studies. Also, it may be relevant to more closely examine specific domains of EF (e.g., decision-making) in terms of weight loss maintenance, as well as specific subgroups of individuals following clinically significant weight loss maintenance (e.g., those performing at the highest and lowest levels of EF). Similarly, while the aspects of psychological functioning, disordered eating, and various sociodemographics that were measured in this study were weakly associated with EF, previous research suggests that the magnitude of these relationships with EF and weight loss outcomes following behavioral treatment should be further explored. Future research may assess the relationship between EF and weight loss maintenance based on additional health criteria or based on whether an individual is in a state of negative energy balance.

5 | CONCLUSIONS

Most individuals with obesity who achieved clinically significant weight loss via behavioral intervention had average or above average EF. Individuals who maintained their lost weight performed better on a test of decision-making than those who regained their lost weight. While replication of these initial findings is warranted with a more generalizable sample, future research should determine whether interventions targeting independent decision-making could have clinical relevance for weight loss maintenance.

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CONFLICT OF INTEREST

None of the authors have any conflicts of interest to report.

AUTHOR CONTRIBUTIONS

Marissa A. Gowey, Gareth R. Dutton, and Virginia G. Wadley conceptualized the study. Gareth R. Dutton was awarded funding for the study. Janice Phillips conducted recruitment and enrollment monitoring. Marissa A. Gowey, William H. Neumeier, and Samantha Henry collected the data. Marissa A. Gowey analyzed the data. All authors contributed to interpretation of the study findings. Marissa A. Gowey, William H. Neumeier, and Gareth R. Dutton drafted the initial manuscript. All authors reviewed, edited, provided feedback, and approved each draft of the manuscript.

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