

Article

Executive function-related improvements on a commercial CBT-based weight management intervention: Pilot randomized controlled trial

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Abstract: Executive functioning is a key component involved in many of the processes necessary for effective weight management behavior change (e.g., setting goals). Cognitive behavioral therapy (CBT) and third-wave CBT (e.g., mindfulness) are considered first-line treatments for obesity, but it is unknown to what extent they can improve or sustain executive functioning. This pilot randomized controlled trial examined if a CBT-based generalized weight management intervention would affect executive functioning and executive function-related brain activity in individuals with obesity or overweight. Participants were randomized to an intervention condition (N=24) that received the Noom Weight program or to a control group (N=26) receiving weekly educational newsletters. EEG measurements were taken during Flanker, Stroop, and N-back tasks at baseline and months 1 through 4. After 4 months, the intervention condition evidenced greater accuracy over time and, to some extent, neural markers of executive function (error-related negativity and beta and gamma band powers) compared to the control group on the Flanker and Stroop tasks. The intervention condition also lost more weight than controls (-7.1 pounds vs. +1.0 pounds). Given mixed evidence on whether CBT-based interventions can change markers of executive function, this study contributes preliminary evidence that a multicomponent CBT-based weight management intervention (i.e., that provide both support for weight management and is based on CBT) can help individuals sustain executive function compared to controls.

Keywords: CBT; obesity; mobile health; executive function; EEG

1. Introduction

Obesity has become increasingly prevalent worldwide, affecting approximately 38.2% of adults in the US, and increases risk of health complications such as type 2 diabetes and cardiovascular disease [1]. Behavioral lifestyle weight management interventions are effective, first-line treatments for obesity [2]. Research is increasingly discovering that the processes implicated in weight management are not just physical, but also cognitive in nature [3]. For example, executive function is a term that describes the cognitive processing and coordination involved in behavioral change, such as planning or inhibition of complex behaviors and performance monitoring [4]. Executive functions are intimately involved in goal setting processes, such as focusing effort towards important weight or eating goals and inhibiting irrelevant behavior or stimuli [5,6]. They are also involved in the coordination and monitoring of weight-related behaviors such

as eating behaviors or physical activity [6]. Overall, this body of work suggests that executive functioning is relevant to effective weight management.

While standard interventions tend to focus on weight-related behaviors and goals, recent research suggests that improving executive functioning could be beneficial for individuals with obesity. Studies and reviews suggest that impaired executive functioning is associated with difficulties losing or maintaining weight [3,6–8]. Further, studies have shown that improvements in executive function are associated with better future weight loss or adherence to healthy behaviors [9–11]. This work raises the possibility that improving or maintaining executive function through weight management interventions could improve weight loss success.

There is mixed evidence on whether weight loss, whether done on one's own or through standard weight management interventions, improves executive function [6,12,13]. In contrast, cognitive remediation therapy for obesity (CRT-O), a type of weight management intervention specifically targeting cognitive processes, has shown stronger evidence of improving executive function [11,14]. For example, one study showed that the effect of CRT-O on behavioral changes (e.g., eating habits) was mediated by improvements in executive function [14]. This suggests that weight management interventions that target cognitive processes related to executive functions could be more helpful than standard non-cognitive interventions. Cognitive behavioral therapy (CBT) is one of the most common evidence-based theoretical frameworks for weight management interventions, and is effective on both in-person and online platforms [15–17]. Previous work suggests that CBT as well as third-wave CBT (e.g., mindfulness) may exert effects on executive function by increasing awareness and monitoring of present thoughts and feelings, recognition and response to conflicts between current and ideal thoughts, and modification of thought patterns [18,19]. Randomized trials have shown that mindfulness interventions increase executive functioning and executive functioning-related brain activity compared to controls [18,20,21]. These were not weight management interventions, however, and to our knowledge, it is unknown whether a CBT-based weight management intervention could improve or sustain executive function.

Therefore, this pilot randomized controlled trial compared executive functioning and neural markers related to executive function in individuals who received a 16 week digital CBT-based weight management intervention (Noom Weight) to a control group who received digital health and weight loss resources. The executive functions required for self-management, self-monitoring, goal setting, and action planning in weight management are commonly measured by computerized cognitive performance tasks. For example, the Flanker task and the Stroop task measure inhibitory control, or the “voluntary inhibition of dominant or automatic responses for controlling actions, thoughts, and emotions [...] in order to respond appropriately to the needs of goal-directed behaviors”, and the N-back task measures working memory [3] and cognitive workload [22]. Further, brain activity in the form of error-related negativity (ERN) or spectral power are thought to represent executive functioning processes, such as inhibitory control and working memory [23,24]. Those exposed to mindfulness training in the context of mental health show greater ERN magnitude and spectral power than controls [25,26]. Thus, in this study, we hypothesized that the intervention group would show better executive function, as measured by the accuracy and reaction time on the Flanker task, Stroop test, and N-back test, compared to a control group over time. We also hypothesized that the intervention group would show increased ERN magnitude (i.e., more negative peak amplitude) and spectral power than the control group over time.

2. Materials and Methods

2.1. Study procedure

This was a prospective single-center, randomized controlled study. The study was approved by the Advarra IRB. Individuals were recruited from social media and from the signup procedure for Noom Weight and had never used Noom before. They were eligible to participate if they were between 18-60 years old, self-reported good health, had overweight or obesity ($\text{BMI} \geq 25$), and could attend in-person visits in Long Island, New York. Exclusion criteria were as follows: a visual impairment that cannot be corrected with glasses or contact lenses; indication of drug, alcohol, or medication abuse; presence of a brain injury, psychiatric disorder, seizure disorders, or other neurological conditions; presence of an eating disorder; and current pregnancy or less than or equal to 6 months postpartum. Once eligible and after providing written informed consent, participants were randomized to either the intervention condition which received the 16 week Noom Weight program ($N=37$), or the control condition ($N=33$). The control condition received a weekly email constraining a newsletter with information on healthy eating, weight loss, and physical activity. There were five monthly in-office visits to gather cognitive performance and EEG measurements. Participants were excluded from data analyses if they attended only one post-baseline visit, for a total sample of $N=50$ (intervention: $N=24$; control: $N=26$). To accurately measure weight, participants were excluded from weight loss analyses if their last visit was more than one month later than the planned visit date, for a total sample of $N=47$ (intervention: $N=23$; control: $N=24$). See Figure 1 for a diagram of inclusion in analyses.

Recruitment for this study occurred during the initial months of the COVID-19 pandemic. For social distancing purposes, participants had the option to attend the in-person visits in a mobile testing center or in an office location in Long Island. The mobile testing center contained seating areas and equipment necessary to run the study and was driven to participants' preferred location. Pre-testing showed adequate EEG data quality in the mobile testing center. Participants were asked to refrain from drinking caffeinated beverages or engaging in vigorous exercise two hours before each visit. At the beginning of each visit, participants were weighed on a scale. Then, the EEG headset was placed on the participant's head. After a 6 minute resting-state EEG was measured, three cognition tests were conducted as follows: practice of 2-back task (3 minutes), 2-back task (20 minutes), break (5 minutes), practice of Stroop task (3 minutes), Stroop task (15 minutes), break (5 minutes), practice of Flanker task (3 minutes), Flanker task (17 minutes), followed by another 6 minute resting-state block.

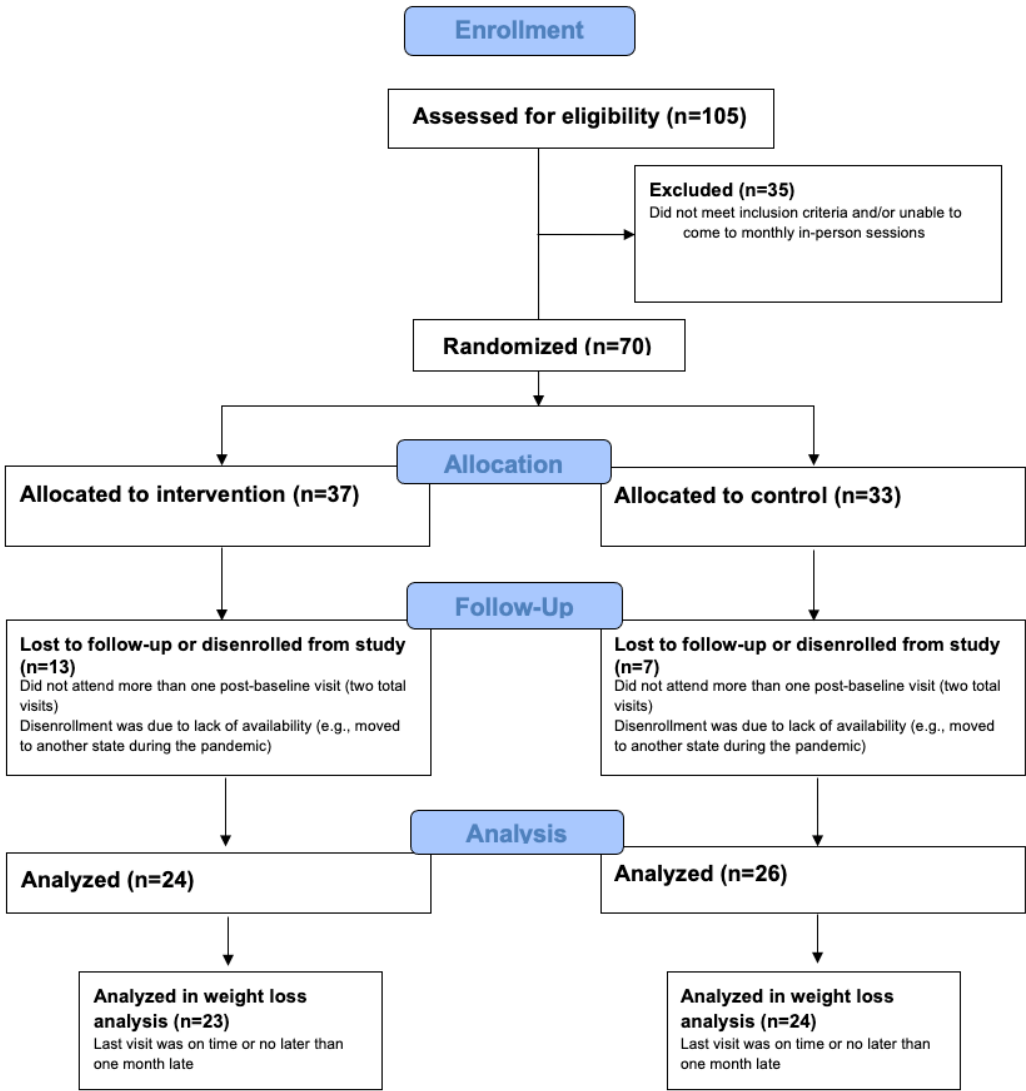


Figure 1. Flow diagram of inclusion and exclusion

2.2. *Intervention*

Noom Weight is a mobile multicomponent behavior change intervention. The intervention provides education and tools surrounding behaviors that have been shown to relate strongly to successful weight management, such as self-monitoring of food or weight, as well as a daily curriculum based on CBT and third-wave CBT techniques. For example, daily interactive articles will define cognitive behavioral therapy and its components (e.g., what are cognitive distortions), and provide practical and applicable examples and activities (e.g., step-by-step identification and reappraisal of a participant’s cognitive distortion). Other articles may describe mindfulness-based approaches and encourage off-line activities such as deep breathing and mindful eating. In addition to the curriculum, individuals gain access to weight and food logging (self-monitoring) features, text message interactions with a human coach, and virtual groups. Coaches are trained in CBT and motivational interviewing techniques and interact with individuals about their weekly progress towards goals. The control group did not receive Noom Weight and instead received weekly emailed newsletters with healthy eating and weight loss tips derived from federal resources, such as the USDA’s Dietary Guidelines for Americans. To reduce potential bias from being randomized to a control group, the newsletters were presented as part of the Noom program.

2.3. Measures

2.3.1. Cognitive tasks

For all cognitive tasks, the sample size for each session was made up of the number of participants who attended each session.

N-back (2-back): The N-back task [27] is a commonly used measure of working memory function [28]. Randomly selected letters were presented one at a time and participants pressed a key based on whether the current letter is the same ("match") or different ("non-match") as the N numbered previous cycle. In this study, a 2-back task was used such that the current letter was compared to the one presented two letters back. In each session, there were 720 total trials and each had a 50% chance of being a "match". Each stimulus (i.e., letter) was presented for 600 ms with 850 ms between stimuli.

Stroop: The Stroop task [29] is widely considered to be a measure of inhibitory control [3]. In the Stroop task, stimuli consist of a word for a color (e.g., "RED") and a font color (e.g., green), which may or may not match the word. Individuals are asked to press a key indicating the color of the word, not the font color. This task involves inhibiting irrelevant and inconsistent stimuli (e.g., the word) and focusing attention on relevant stimuli (e.g., the font color). In this study, three colors were used (green, red, and blue). Three trial types were used: congruent, incongruent, and neutral. In congruent trials, red and/or green words and font color matched. In incongruent trials, red and/or green words and font color did not match. In neutral trials with red or green words and blue font color, participants did not need to respond. Stimuli were presented randomly within each trial type. In each session, there were 112 trials of each condition. The duration of each stimulus was 200ms with 2000-2400 ms in between stimuli. To ascertain accuracy, the number of correct, incorrect, and no response occurrences for each trial type were averaged across trials; reaction time was averaged per response and trial type.

Flanker: The Flanker task is based on the Erikson paradigm, another common measure of inhibitory control [3]. This task typically consists of a right-facing or left-facing arrow that is immediately surrounded by arrows that all face the same direction (e.g., all facing right or all facing left). Individuals are to press a key indicating the direction of the target arrow. Two trial types were used. In congruent trials, the surrounding arrows faced the same direction as the target arrow, while in incongruent trials, the surrounding arrows faced the opposite direction. Each session consisted of 315 trials of each trial type. Stimulus duration was 150 ms.

Two measures were collected for each cognitive task. To ascertain accuracy, the number of correct, incorrect, and no response occurrences for each trial type (e.g., incongruent correct vs. incongruent incorrect vs. incongruent no response) were averaged across trials. In addition, reaction time (in milliseconds) was also averaged per response and trial type.

2.3.2. Brain activity

EEG measurement and preprocessing: As typically done [30], EEG measurement was performed during the cognitive tasks to capture electrical activity in response to cognitive stimuli. EEG data were collected at each visit for 5 total visits. EEG data were sampled at 300 Hz at Fz, Cz, and Pz channels using a Wearable Sensing DSI-24 dry electrode system. Each trial was separated and categorized by condition (e.g., congruent or incongruent) and by response accuracy (e.g., correct or incorrect). In order to obtain

enough trial data for statistical analyses, we combined condition types to focus on correct vs. incorrect responses. Individual trials were extracted -300s to 1000ms relative to response onset. Each trial subtracted the pre-response baseline EEG signal voltage, averaged from -300ms to 0ms before the response occurred. EEG measurements included error-related negativity (ERN) and power spectra, which are considered markers of executive functioning [23,31,32].

Standard preprocessing were run on Neuropype (neuropype.io), an EEG/biosignal data processing and collection platform by Intheon, to clean data and remove artifacts (e.g., blinks, movement). The details of the preprocessing chain are published elsewhere [33] but are presented here in brief: high-pass filter at 0.5 Hz, removal of bad channels using neighboring channel correlation and high-frequency noise detection, removal of high-artifact time windows using Artifact Subspace Reconstruction with an artifact threshold of 10 s.d., low-pass filter at 45 Hz, channel re-interpolation, and common average re-referencing. The Fz, Cz, and Pz channels analyzed in this study had adequate data quality and showed little evidence of residual blink artifacts; however, the data showed a moderate amount of noise overall, reducing the sample size and statistical power of some EEG analyses. The analyses reported below only contain EEG data that had adequate data quality (i.e., absence of blink artifacts).

ERN: The ERN is a negative deflection occurring around 100 ms after response (Ghering et al., 1993). Increased (i.e., more negative) magnitude of ERN amplitudes after errors are thought to constitute better executive functioning in the form of cognitive control and monitoring and cognitive flexibility [23]. To avoid detection of inaccurate peak amplitudes [34], a wavelet-based peak finding method was applied to the session mean ERN waveform within 0 to 300ms relative to response onset. The ERN peak amplitude and latency values were identified.

Power Spectra and Frequency Bands: The Multitaper method was used to estimate power spectral density for each trial from 0 to 500ms relative to response onset. The PSD was normalized to account for 1/frequency fall-off and converted to decibels (dB). The normalized PSD was further averaged within frequency bands to yield bandpower estimates for the following frequency bands: delta: 1-3 Hz, theta: 4-7 Hz, alpha: 8-12 Hz, beta: 13-32 Hz, and gamma: 33-50 Hz. Increased power, especially alpha and beta power, are linked to better cognitive control and attention [35–37].

2.4. Statistical analysis

Intheon (intheon.io) analyzed the data using their Neuroscale Insights biosignal data analytics platform (neuroscale.io) and were blinded to condition. For cognitive tasks, 2 factor mixed effects ANOVA models were conducted with condition, session number, and the condition and session interaction as main effects and the cognitive task reaction time or accuracy as the dependent variable. The False Discovery Rate (FDR) method [38] corrected for multiple comparisons. For EEG analyses, linear mixed models were used since they are robust to missing data at random [39]. Each univariate EEG feature was the dependent variable, with fixed effects of condition (between-subjects factor), session number (within-subject factor), and the interaction of condition and session. A random slope was included for each participant. A mass-univariate approach, as typical for analyzing ERNs, was used to examine the effects of each factor on each EEG feature (e.g., ERN amplitude for a given channel at a specific session, or power spectral density at a specific frequency and/or session) independently. The FDR method corrected for multiple comparisons across features for each EEG channel, and not across EEG channels. Additionally, post-hoc testing was conducted to compare changes over the intervention from baseline to end of treatment. We used t-tests in a 2x2 factorial design: intervention vs. control (unpaired t-tests) and Session 1 vs. Session 5 (paired t-

tests) with FDR correction for multiple comparisons. Weight loss was analyzed using paired-sample t-tests to compare weight at baseline and from visit 5 (week 16).

3. Results

3.1. Baseline characteristics and weight loss

The intervention and control conditions did not significantly differ on any of the baseline characteristics of gender, age, baseline BMI, baseline weight, ethnicity, educational status, and employment status (see Table 1). Compared to baseline, the intervention group lost 7.1 pounds (SD = 9.4; -3.6% body weight) at 4 months, while the control group gained 1.0 pounds (SD = 17.5; +0.43% body weight) ($t(45)=-2.03$, $p=.05$).

Table 1. Demographics and baseline characteristics

	Intervention	Control	p-value
Gender			.99
Female	22 (88%)	20 (83.3%)	
Male	3 (12%)	4 (16.7%)	
Age	46.3	42.1	.09
Baseline bmi	33.0	36.1	0.2
Baseline Weight (kg)	90.4	103.0	0.06
Ethnicity			.30
Asian or Pacific Islander	3 (12%)	0	
Black/African	3 (12%)	1 (4.2%)	
Caucasian	15 (60%)	19 (79.2%)	
Hispanic/Latino	2 (8%)	3 (12.5%)	
Other	2 (8%)	1 (4.2%)	
Education			.50
High school degree	1 (4%)	2 (8.3%)	
Some college	4 (16%)	3 (12.5%)	
2-year college degree or vocational training	1 (4%)	4 (16.7%)	
4-year college degree	9 (36%)	5 (20.8%)	

Graduate degree (Master's, PhD, MD, JD)	10 (40%)	10 (41.7%)	
Employment status			.20
Full-time employed	17 (68%)	21 (87.5%)	
Part-time employed	5 (20%)	0 (0%)	
Self-employed	1 (4%)	1 (4.2%)	
Unemployed	0 (0%)	1 (4.2%)	
Looking after family	2 (8%)	1 (4.2%)	

3.2. Cognitive tasks

3.2.1. 2-back

There were no significant differences for condition or interactions of condition and session. There were significant main effects of session for correct matches ($\beta(5, 211)=4.91$, $t=8.45$, $p<.001$) and correct rejections of non-matches ($\beta(5, 211)=5.04$, $t=8.70$, $p<.001$) in which accuracy improved over time for the whole sample. No responses also decreased over time for both match and non-match trials ($\beta(5, 211)=-4.28$, $t=-6.14$, $p<.001$; $\beta(5, 211)=-4.51$, $t=-6.45$, $p<.001$).

3.2.2. Stroop

Accuracy. There was no main effect of condition (all $ps > .12$). There was a main effect of session in which accuracy decreased over time for congruent incorrect ($t=3.23$, $p=.001$), congruent correct ($t=-5.41$, $p<.001$), and incongruent correct ($\beta(5, 148)=0.66$, $t=-3.30$, $p<.001$) trials. This was qualified by a significant group by session interaction for congruent correct trials (Figure 2; $\beta(5, 148)=1.56$, $t=2.53$, $p=.01$) in which the control group decreased in accuracy while the intervention group sustained accuracy. There were also significant main effect of session for congruent no response ($\beta(5, 148)=1.71$, $t=4.59$, $p<.001$) and incongruent no response ($\beta(5, 148)=1.61$, $t=-4.28$, $p<.001$) trials suggesting increased no response over time. Significant group by session interactions for congruent ($\beta(5, 148)=-1.30$, $t=-2.47$, $p=.01$) and incongruent ($\beta(5, 148)=-1.12$, $t=-2.10$, $p=.03$) no response trials suggested that this main effect was driven primarily by an increase in no response from the control group.

Reaction time. For reaction times, there was a significant main effect of condition for incongruent correct ($\beta(5, 148)=123.79$, $t=3.01$, $p=.003$) and congruent correct ($\beta(5, 148)=105.73$, $t=2.82$, $p=.005$) trials in which the intervention group had faster reaction times than the control group. These were qualified by significant interaction effects for both congruent ($\beta(5, 148)=-17.06$, $t=-2.85$, $p=.004$) and incongruent correct ($\beta(5, 148)=-19.20$, $t=-3.30$, $p<.001$) trials in which the intervention group showed faster reaction times over time while the control group did not change over time. There were no significant main effects for session (all $ps > .11$).

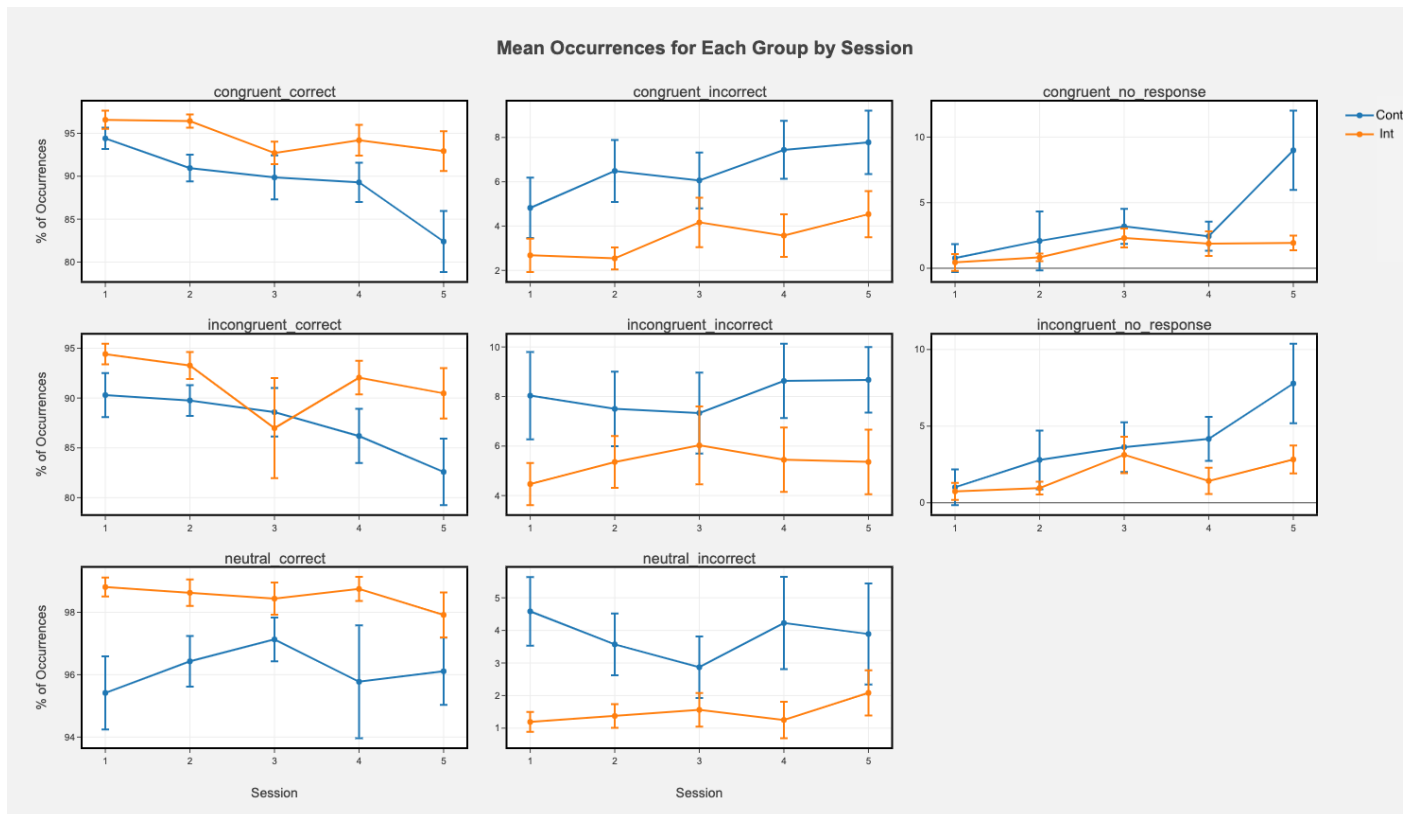


Figure 2. Mean occurrences (%) of each trial type for each group by session in the Stroop task.

Note. Greater % of correct trials means greater accuracy, while greater % of incorrect means lower accuracy (more errors). Error bars represent +/- SEM. Cont represents the control condition and Int represents the intervention condition.

3.2.3. Flanker

Accuracy. There was a main effect of session indicating that for the entire sample, accuracy decreased over time in congruent correct ($\beta(5, 213)=-1.46$, $t=-3.06$, $p<.001$) trials and incongruent correct ($\beta(5, 213)=-1.18$, $t=-2.29$, $p=0.03$) trials. There was also a main effect of condition in which the control condition showed lower accuracy than the intervention condition for incongruent incorrect trials ($\beta(5, 213)=-9.60$, $t=-2.45$, $p=0.01$) and incongruent correct trials ($\beta(5, 213)=9.39$, $t=2.14$, $p=0.03$). The interactions suggest that this was driven primarily by sustained or increased accuracy over time in the intervention group but declining accuracy in the control group (Figure 3; incongruent correct: $\beta(5, 213)=1.59$, $t=2.19$, $p=0.03$; congruent correct: $\beta(5, 213)=1.13$, $t=1.67$, $p=.09$; Figure 2). There were also main effects of session for congruent ($\beta(5, 213)=1.00$, $t=2.61$, $p=0.009$) and incongruent no response ($\beta(5, 213)=0.94$, $t=2.43$, $p=0.01$) trials in which no responses increased over time for the whole sample. Main effects of condition for no response trials were not significant (all $p>.91$). There were trending, nonsignificant interactions in which the control group showed more no response over time and the interaction group was steady (congruent no response: $\beta(5, 213)=-0.84$, $t=-1.55$, $p=.12$; incongruent no response: $\beta(5, 213)=-0.77$, $t=-1.41$, $p=.16$).

Reaction time. There was a marginally significant main effect of session for congruent correct ($\beta(5, 213)=-5.27$, $t=-1.81$, $p=.07$) trials, with a significant effect for incongruent correct trials ($\beta(5, 213)=-9.57$, $t=-3.12$, $p=.002$) indicating that reaction times decreased over time for the entire sample. There was also a marginally significant main effect of condition for congruent incorrect ($\beta(5, 213)=79.94$, $t=1.66$, $p=.10$) and incongruent correct trials ($\beta(5, 213)=53.03$, $t=1.93$, $p=.053$) in which the intervention condition had faster reaction times than the control condition across trials. There were

marginally significant interactions in which the control condition showed slower reaction time over time and the intervention condition was stable for congruent correct ($\beta(5, 213)=8.22$, $t=1.93$, $p=.053$) and incongruent incorrect ($\beta(5, 213)=9.21$, $t=1.61$, $p=.11$) sessions.

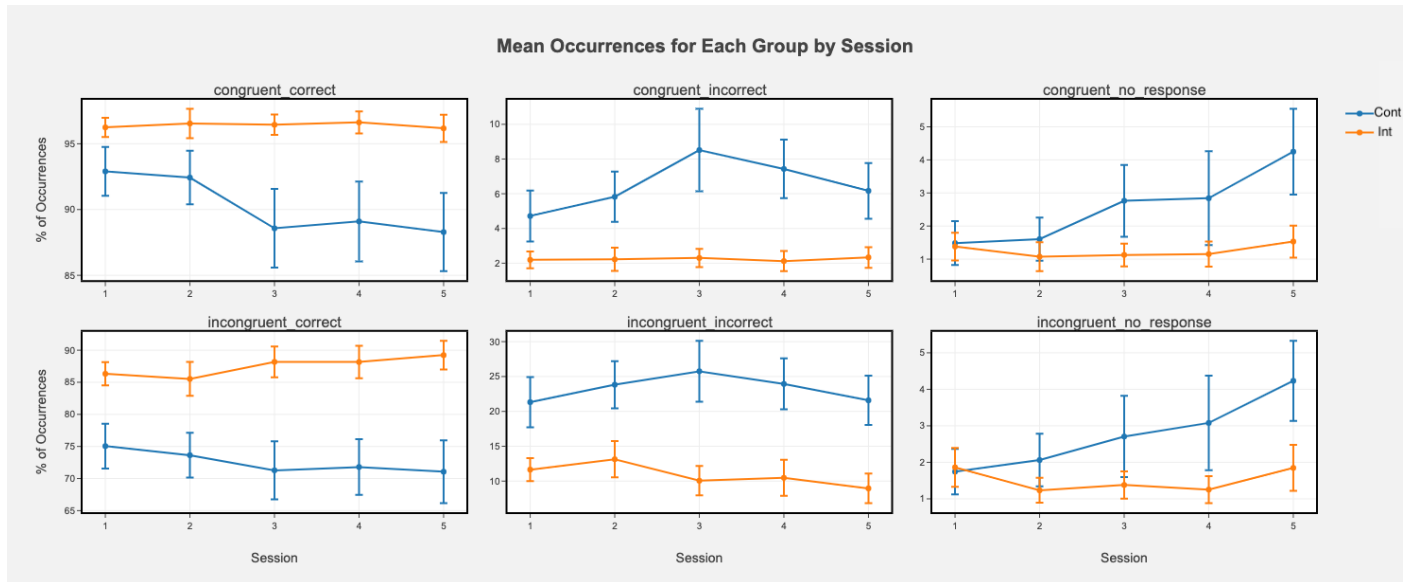


Figure 3. Mean occurrences (%) of each trial type for each group by session in the Flanker task.

Note. Greater % of correct trials means greater accuracy, while greater % of incorrect means lower accuracy (more errors). Error bars represent \pm SEM. Error bars represent \pm SEM. Cont represents the control condition and Int represents the intervention condition.

3.3 Brain activity

ERN waveforms are displayed in Figure 4.

3.3.1. 2-back

EEG results were unable to be analyzed due to the overall poor performance (e.g. large number of no responses) across most subjects on the task which created too few correct and incorrect trials for comparisons of the ERN response.

3.3.2. Stroop

There was no significant main effect of condition for ERN peak amplitude or latency. There was a marginally significant condition by session interaction ($\beta(5, 148)=-0.55$, $t=-1.76$, $p=.08$; $\beta(5, 148)=0.01$, $t=2.00$, $p=.08$, respectively) for incorrect trials in peak amplitude in the Fz region. The t-tests from this mixed model, though not significant, provided insight into the direction of the interactions, in which Fz peak amplitude decreased (i.e., the magnitude of the ERN increased) from session 1 to session 5 for the intervention group, but not for the control group. For latency, Fz peak latency shifted earlier at session 5 compared to session 1 for the control group, but for the intervention group, latency shifted later at session 5 compared to session 1.

There was a significant main effect for condition for Pz beta ($\beta(5, 148)=2.34$, $t=2.51$, $p=0.03$) and gamma ($\beta(5, 148)=3.43$, $t=2.97$, $p=0.01$) band powers for incorrect trials. The intervention group showed increased power compared to the control group. No interactions of condition and session were significant.

3.3.2. Flanker

There were no significant main effects of condition for peak amplitude and latency. There was greater ERN magnitude (i.e., more negative peak amplitude) in the Cz region during incorrect responses in the intervention group compared to the control ($\beta(5, 213) = -1.96$, $t = -1.36$, $p = .35$), but this was not significant with FDR adjustment.

4. Discussion

This pilot RCT provides preliminary evidence that this mobile CBT-based intervention helped to maintain or improve executive function over time compared to a control group. Specifically, the intervention group showed better sustained performance on executive function-related cognitive tasks compared to a control group, which showed decreased or no improvement in performance. Further, the intervention group showed a few changes (i.e., greater reactivity) in executive function-related brain activity. Finally, the intervention group lost significantly more weight at 16 weeks than the control group. Overall, these results of greater performance and brain activity in the intervention group are in line with other mindfulness interventions in other contexts (i.e., not weight management), as well as weight interventions such as CRT-O that focused primarily on cognitive training [18,20,21,11,14]. To our knowledge, this is the first study to find that a CBT-based generalized weight management intervention resulted in these differences. These effects seem to be due to the CBT-based program rather than solely engagement in weight loss practices (e.g., physical activity or healthy eating), since the control group also received weight loss guidance from public resources and was derived of individuals motivated to participate in a weight loss study. This suggests that CBT and third-wave CBT focusing on cognitive-related processes, in combination with providing support and information about standard behavioral weight management best practices (e.g., goal setting, self-monitoring), can be beneficial for sustained executive function. This has implications for future work and interventions given that executive functioning can predict weight loss success and improvements in executive functioning are related to greater weight loss.

4.1 Cognitive tasks

We found that the intervention group had higher accuracy overall and over time in the Flanker test for incongruent trials, which tend to involve inhibitory control and conflict monitoring processes. Inspection of the plots suggests that the control group decreased in accuracy over time and the intervention group was able to sustain accuracy. These results suggest that the intervention enabled sustained inhibitory control over time, in contrast to declines in the control group.

In the Stroop task measuring inhibitory control and conflict monitoring, the intervention group maintained accuracy in congruent correct trials while the control group decreased in accuracy. The control group also failed to provide a response increasingly over time while the intervention group remained consistent. The intervention group also showed faster reaction times than the control group for congruent and incongruent correct trials. The intervention group showed faster reaction times over time while the control group did not. Thus, in both the Flanker and Stroop tasks, the intervention group had better performance over time in congruent correct responses. Taken together, these results suggest that the intervention helped individuals to maintain inhibitory control in comparison to the control group which showed declines over time in accuracy and reaction time.

To our knowledge, it is unknown to what extent individuals with obesity sustain performance on multiple, separated cognitive tasks over time periods as long as a month. We speculate that mental fatigue may explain the control condition's decline in performance over time for the Flanker and Stroop tasks. There is evidence suggestive

that obesity could be related to greater experienced and perceived mental fatigue [40–44]. In current study, the 2-back task was always completed first, followed by the Stroop and Flanker tasks. The 2-back task is the most difficult of the cognitive tasks in this study and has been shown to induce mental fatigue and declines in performance [45]. Despite the task's difficulty, both conditions were able to improve their performance over time. Thus, it is possible that the attention required to perform increasingly better on this task may have led to greater fatigue on subsequent tasks and therefore declining performance (Stroop and Flanker) in individuals with obesity without cognitive intervention, as in the control group. In contrast, perhaps CBT and mindfulness helped to sustain the intervention condition's attention and perseverance. Future studies should confirm this potential explanation.

We did not find group differences or interactions for the N-back test. This could be because the N-back is a very difficult cognitive task and accuracy was poor overall for this task; this may have reduced differences between the groups. Another potential explanation is that the 2-back test measures working memory while the Flanker and Stroop task are more associated with inhibitory control and conflict monitoring. It may be possible that CBT-based interventions do not affect working memory as much as inhibitory control, as a meta-analysis found that mindfulness interventions improved executive functions like inhibitory control but not working memory [46], and another study found that a CBT intervention led to improvements primarily in inhibitory control (i.e., Stroop performance) but not other components of executive function (Delgado-Rico et al., 2012). Future studies should examine this further.

Overall, these results align with previous studies of CBT and mindfulness interventions in other domains that have shown improvements in higher-order executive functions such as inhibitory control as measured by the Stroop and Flanker tasks [47–49,46].

4.2 Brain activity

During the Stroop test, Pz beta and gamma band powers in incorrect trials were significantly greater for the intervention group than the control group. Frontal and parietal beta power have been linked to increased cognitive control, attentiveness and attentive control, planning, memory [50,32,51]. This corroborates previous studies, which have shown that mindfulness interventions can increase beta power compared to controls and that meditators show higher gamma power than controls [52–54]. There was also a trend towards greater Fz ERN magnitude in the intervention group. Generally, greater ERN magnitudes (i.e., more negative peak amplitudes) are seen as reflections of better performance and conflict monitoring [23], but greater ERN magnitudes on the same task over time could be indicative of more efficient and adaptable processing [55]. In this case, ERN magnitudes in the control group did not increase, which may suggest more efficient processing and control of resources in the intervention group.

For the Flanker test, for which EEG data quality was noisier than the Stroop test, there were trends towards greater ERN magnitude in the Cz region and theta band power on incorrect trials in the intervention condition, but these were not significant. Greater ERN responses following errors is indicative of efficient cognitive information processing and control [56]. Theta band power is reflective of conflict monitoring and strategic control [57,58].

Previous work suggests that electrical brain activity is not easily malleable and does not always change from pre- to post-intervention. For example, some CBT interventions in other contexts found no change in ERNs pre and post-intervention, despite improvement in symptoms (e.g., anxiety, OCD; [59–61]. In contrast, mindfulness interventions have shown better success in changing ERN magnitudes [21,25]. Researchers argue that this is because mindfulness interventions directly target cognitive processes

that would enable ERN changes, such as in-the-moment monitoring and inhibition [25]. They contend that this could be why growing numbers of mindfulness-based studies have demonstrated significant pre- to post- ERN changes in an intervention group compared to a control group, but CBT-only interventions (i.e., without mindfulness components) have not [62]. Given this context of past work and remaining questions, this study contributes additional data on the effect of a multicomponent CBT-based intervention and shows evidence of neural activity changes when CBT and mindfulness are involved with generalized weight management support. This is in line with previous findings that adding a Mediterranean-based diet to caloric restriction resulted in greater executive functioning and brain activity than caloric restriction alone [63]; this highlights the effect of adding cognitive-related components to general weight management strategies. Further, researchers speculate that the amount of exposure and intensity of the intervention could determine whether brain activity changes will occur [25]. This notion is based on mixed evidence for pre- to post- changes in electrical brain activity after one-session mindfulness sessions, but stronger evidence for longer mindfulness interventions [64,65]. Putting this evidence together, then, it may be that this CBT-based intervention showed evidence of some changes in brain activity because it was a 16 week long intervention with many opportunities to engage in the cognitive processes that eventually lead to the executive processes represented by these neural markers. Future work should test this speculation.

4.3 Limitations

Limitations of this study include lower signal quality in the study data compared to data quality pre-testing, most likely due to the use of the mobile testing center, which was necessitated by the start of the COVID-19 pandemic. However, this affected all sessions equally, so it did not differentially impact some tasks or sessions over others. Another limitation is that EEG analysis could not be conducted on the 2-back task because of the prominence of no response trials, as error responses are necessary to analyze the ERN component. This could be due to the difficulty of the N-back test as participants qualitatively reported that they found it to be exceptionally challenging. Moreover, this study also had a small overall sample size with high initial dropout after randomization, most likely due to the start of the COVID-19 pandemic. As a result, there were nonsignificant trends in the data that future studies should confirm with larger sample sizes. Finally, the participants were more educated and higher income than the general population, so future studies should determine how generalizable the results are to other populations.

5. Conclusions

A CBT-based generalized weight management intervention resulted in sustained executive functioning compared to a control group. Specifically, the intervention group showed evidence of increased inhibitory control and performance monitoring and, to some extent, executive function-related brain activity. Our results contribute data to the mixed literature on CBT interventions and pre-post changes in executive function or brain activity. Future studies should examine what mediates these improvements, as well as explore if our results generalize to other populations or CBT-based behavior change interventions.

Author Contributions: Conceptualization, A.M., E.S.M., H.B., and G.H.; methodology, G.H.; software, G.H.; formal analysis, G.H. and J.L.; investigation, A.S.H.; resources, A.M.; writing—original draft preparation, A.S.H.; writing—review and editing, A.S.H., A.M., E.S.M., H.B., G.H., J.L.; visualization, G.H.; supervision, A.M., E.S.M.; project administration, H.B., S.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Advarra Institutional Review Board (protocol code 00017566).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Restrictions apply to the availability of these data. Data were obtained from Noom and are available by request from the corresponding author with the permission of Noom.

Acknowledgments: We thank Intheon for their expertise related to implementation of cognitive tasks and EEG.

Conflicts of Interest: Authors A.M., E.S.M., H.B., and A.S.H. are employees of Noom Inc and have received salary and/or stock compensation from Noom, Inc. J.L. was a contractor for Noom at the time this manuscript was prepared, but did not receive stock options and is no longer affiliated with Noom. G.H. is an employee of Intheon.

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